Senior Thesis

GROUND WATER AND SUBSURFACE CONTAMINATION EXERCISES

by
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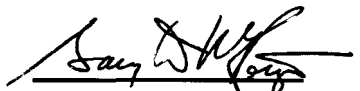
Approved by:



Dr. Garry McKenzie

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Chapter 1: Introduction and Basic Geological Processes

Introduction to Units

The purpose of this senior thesis is to demonstrate the basic geological parameters affecting the distribution and flow of ground water, and how these parameters interact with subsurface contaminants. The units comprising this thesis contain exercises that are designed to teach concepts used in ground water studies and remediation. The concepts are presented in two units that include a discussion of the concepts presented in each particular unit and related exercises that illustrate those concepts. The exercises contain illustrations and tables, and are characterized by simple maps and cross sections. Such information provides data for the operation of formulas used in calculating various hydrogeological parameters and in working through the exercises.

The overall object of the units is to show how ground-water and contaminant flow are predicted, thereby providing a unified picture of the basic concepts in hydrogeology and ground-water pollution. Remediation methods will also be discussed. U.S. Environmental Protection Agency (EPA) technology transfer handbooks and workshop and seminar summaries are used as the basis of this work. This group of exercises is designed for second-year earth science students and other professional personnel, such as managers, city council members, etc. The exercises accompanying the units are in the appendices.

Discussion of Basic Geological Processes

Due to the limited ground-water resources in existence and the ever-increasing demand for water, there is an urgent need to protect unpolluted ground waters, and to remediate (where possible) polluted aquifers and soil. In order to predict the distribution and fate of contaminants, much information must be known: the occurrence and distribution of ground water, the nature of geologic materials and aquifer(s), boundary conditions, and confining units in the area of interest.

Ground-water contaminants and geologic materials vary greatly in their properties. In this portion of the introduction, a brief overview of geologic processes which are limited to materials, systems, and environments appropriate to this study are provided. Sediment-filled river valleys have been a common location for agricultural, manufacturing, and transport activities and communities. Many contaminant sites are located within this environment. To support these activities water is withdrawn from aquifers in sediments or sedimentary rocks in these valleys. In the same environments, potential contaminants are used and disposed of. The other major groups of rocks, igneous and metamorphic, are not major water-bearing units. Water and contaminant flow in these rock units is often confined to fracture channels. Flow in fractured

media is complex, difficult to sample and model, and beyond the scope of this work. Thus it deals primarily with sediments and sedimentary rocks.

Sedimentary rocks are composed of sedimentary particles derived from other rocks, or compounds precipitated out of water by various processes or organisms. These sedimentary particles, which vary in size from glacial boulders to fine oozes, are laid down (usually in a horizontal orientation) in a sediment depositional system. Commonly, soils, poorly consolidated sediments, and fragmented rock overlie bedrock. Sedimentary rocks are also composed of sedimentary particles turned to rock by compaction, mineralogical changes, cementation, and de-watering. Depositional systems vary greatly in their areal extent and workings, and this variation controls the properties of the sediments or the rocks formed from them. If the depositional system of the rock or sediment is of limited areal extent, or characterized by sediments of different sizes or properties, one would find the ground-water flow through such a region to be more complex than that in a unit or series of units that were very homogeneous and widespread. Sediments and sedimentary rocks can bury an eroded bedrock surface with lower permeability and porosity. Determining the nature and configuration of that buried surface is very important due to its effects on the movement of fluids in aquifers above it. Figures 1 and 2 show examples of two sediment depositional systems and underlying rock units. One can see that an understanding of the nature and geologic history of an area aids in the characterization of a site's hydrogeology. The characterization of a contaminant site in hydrogeological terms is paramount in determining the extent of the contamination problem and the most effective and realistic cleanup.

As noted above, most sedimentary rock units are deposited in overall horizontal layers or beds. Subsequent ground-water flow through rock units tends to parallel the bedding planes, if there is a noticeable difference in hydraulic conductivity (permeability) between the units and if the units remain horizontal.

The make-up and structure of contaminated geological materials are of major importance in the determination of how those contaminants move and what eventually happens to them. It is beyond the scope of this paper to examine geology, except as particulars in a model site or to illustrate hydrogeologic principles. Geological conditions dealt with in this work have been chosen because they are typical, elementary, or best illustrate a particular concept. The typical situation presented is one of unconsolidated sediments overlying sedimentary rock units of varying permeability.

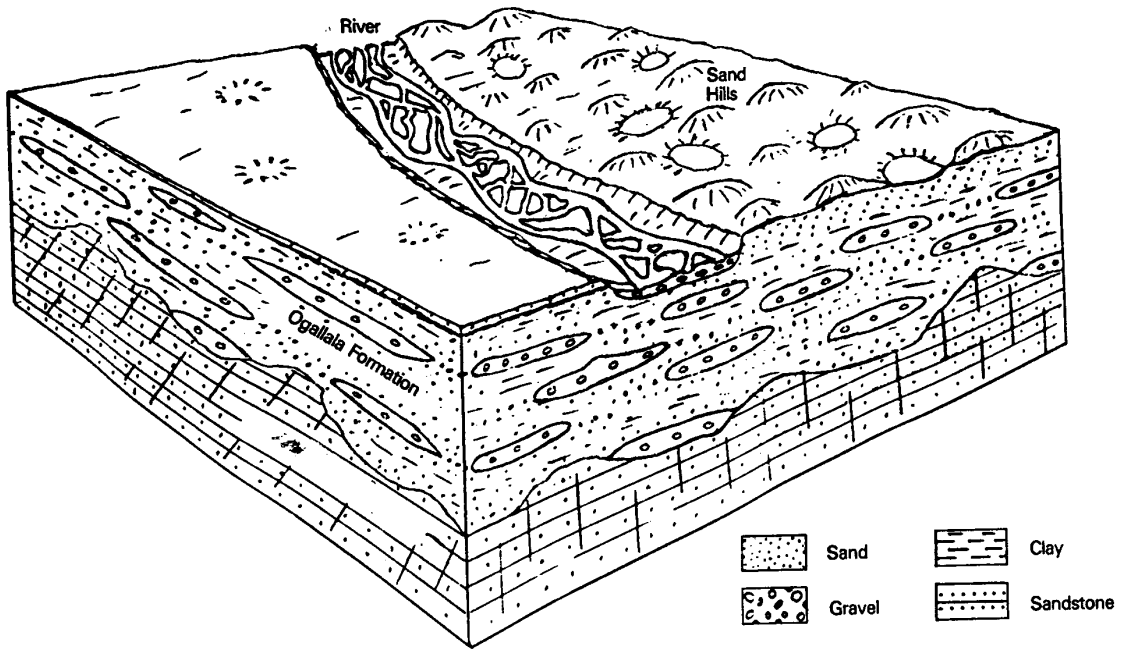


Figure 1: Block schematic of typical sand and gravel units overlying bedrock (U.S. EPA, 1987, from Heath, 1984).

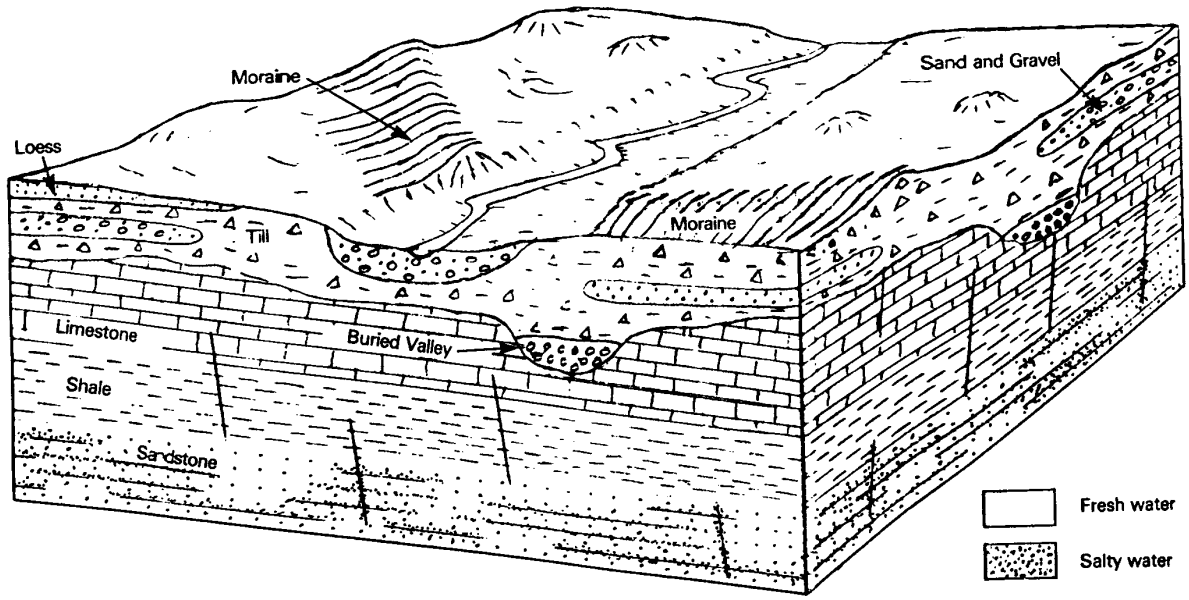


Figure 2: Block schematic of typical geologic units in a glaciated area (U.S. EPA, 1987, from Heath, 1984).

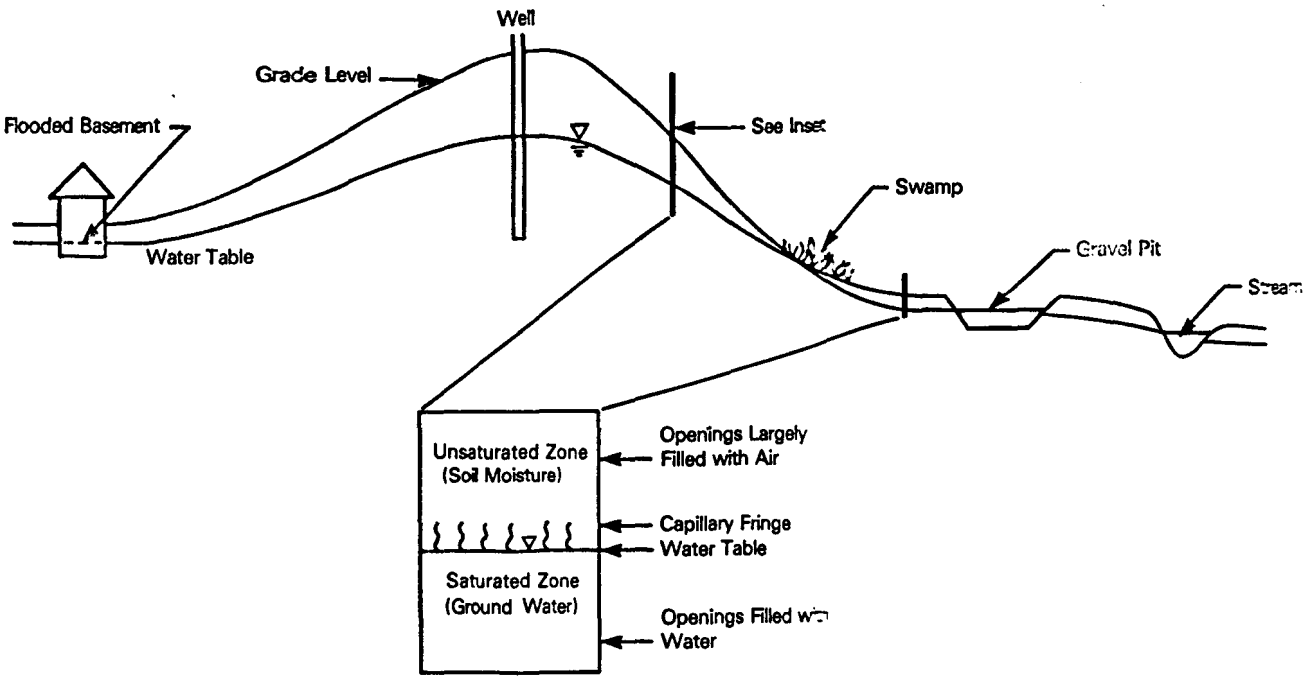


Figure 3: Water table typically mirrors the surface topography to some extent. Note detail of the capillary fringe (U.S. EPA, 1987).

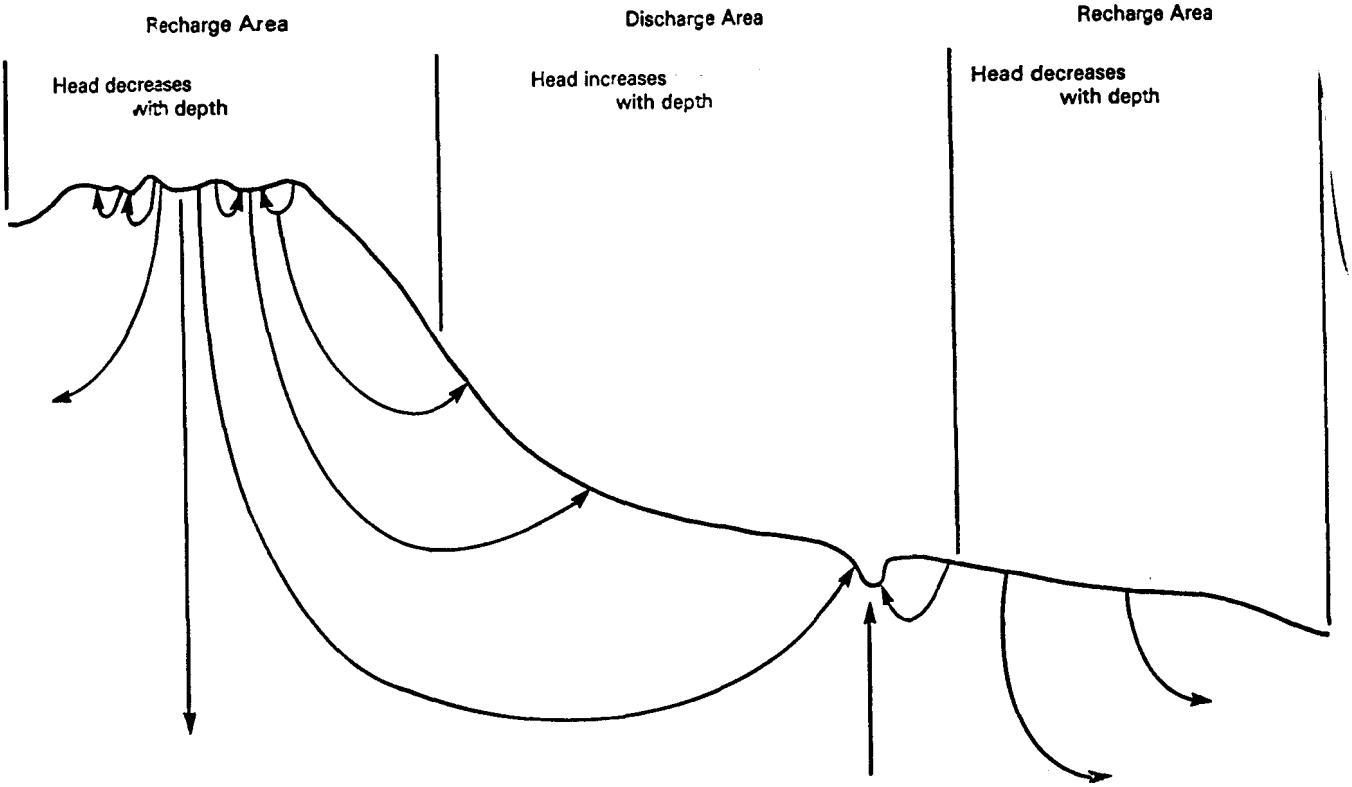


Figure 4: Cross section through varied topography showing a highland recharge area and a lower elevation discharge area. Ground-water flow paths are shown (after U.S. EPA, 1987).

Chapter 2 - Unit A: Ground Water Occurrence in the Geological Environment

Introduction

This unit investigates the occurrence and movement of subsurface water, and how water in the subsurface is mapped. How geologic materials affect the occurrence of ground water, and some ways that geological information can be presented are also discussed. The actual exercises for Unit A are in Appendix I.

The Water Table

Most geologic materials contain voids or pores, and it is within these pores that ground-water exists and moves. Underground water occurs as soil moisture in the zone above the water table, where the pores contain both air and water. This zone is known as the unsaturated zone, or sometimes the zone of aeration. In most areas there is a distinct water table, the upper surface of the underground body of water in which all pore spaces are filled with water. The unsaturated zone drains by gravity to the water table, but some moisture remains on the sides of pores and between grains. This remaining water is known as residual saturation and has effects on the movement of contaminants and water through the unsaturated zone. The material just above the saturated zone is saturated, but has a negative hydraulic pressure. The mass of water in this thin volume is in place due to the wicking action of the pores of that geologic material. This area is known as the capillary fringe (Figure 3).

The water table generally conforms to the contours of the land surface. Gravity is constantly acting to draw the water from "mounds" underlying high areas down to low areas, leveling the water table. Recharge from rainfall and surface water bodies serves to replenish water under the high areas (Figure 4). That the water table is not flat is due to the resistance to underground flow of water by soil and rocks. The water table typically ranges from 0 to 40 feet in humid areas, and down to hundreds of feet in more arid areas (U.S. EPA, 1987).

The water table intersects the ground surface in swamps and is equal in elevation to the water level in excavations (for quarries, highway borrow pits, or building foundations). The depth of the water level in wells (usually given as an elevation above sea level, similar to land contours) can also be measured. Surface bodies of water can show false water-table elevations if affected by surface waters flowing into them (surface run-off) from a larger area of ground than they themselves occupy. That is, if a stormwater drain from a parking lot empties into a pond, or a river draining a valley empties into a lake, the water level in the pond or lake can be higher than the adjacent water table. Under the driving force of gravity river or pond water will seep down (infiltrate) through the underlying sediments or rock to the water table, . This seepage rate

will often be slower, sometimes much slower, than the rate that run-off from the parking lot or river refills the pond or lake. If the surface body of water is contaminated, the aquifer may also become contaminated (Figure 5).

The water volumes (and levels) in surface bodies and aquifers fluctuate according to recharge and discharge rates. Stream, river, and lake water levels are related to ground water in that the water level in them can be above, level with, or below the water table. If the river or lake bed is below the water table, typically due to erosion or a rise in the ground-water level due to heavy rain or snow recharge the saturated zone discharges to those surface bodies of water. Ground-water will seep up through the bed, or leak from springs along a riverbank or shoreline.

In the case of rivers and lakes, the level often depends on the influx of water from creeks, streams, and other rivers. For an aquifer the levels change due to loss or gain from surface bodies of water, infiltration of rainfall through the unsaturated zone, and through loss due to drying of overlying soil and roots of vegetation. The term for the latter discharge path is evapotranspiration. Knowing the locations and amounts of ground-water recharge and discharge is important, because of the effects on the water table level, the dilution it causes in the ground water, and the possibility of leaching contaminants from the surface or unsaturated zone.

Aquifers

A rock or sediment layer that transmits water at a rate fast enough to form a viable source for use at a spring or when a well is drilled is known as an aquifer. Layers or areas that are nearly impermeable to water, or transmit it very slowly, are called aquitards. The term for the ability of a geologic unit to transmit water is known as permeability or hydraulic conductivity. Units with low permeability or hydraulic conductivity do not allow water to pass through them as easily as those with high permeability.

Ground water in aquifers occurs in two basic scenarios: the unconfined aquifer and the confined aquifer. The unconfined type is analogous to a kiddie pool filled with much sand and not as much water. The "water table" can be found by digging a hole or poking in a stick and seeing how much length is wet, much like a well. The water surface (under the sand surface) is free to rise and fall according to recharge and discharge. To use the same pool analogy to model a confined aquifer, water could be added until it just covers the sand. A different, low permeability geologic material is required to confine the water in the aquifer. An old plastic sheet with a few tiny holes would be placed over the sand/water layer, and the pool filled to the top with silty mud and allowed to dry. The sand aquifer is confined; very little water can flow upwards through the plastic. If one was to stand atop the hardened mud and poke a tube (a "well") down through the layers, including the plastic, the water would be forced up just a bit into the tube, above the level of the plastic sheet due to one's body weight. This rise in the water level above the plastic layer

represents hydraulic head or pressure. This analogy has some flaws, the main being that true hydraulic head comes primarily from the mounding in higher topographic areas, and from recharge areas in the higher elevation of the confined aquifer (not just from a giant's bodyweight). In reality, the weight of the overburden can add to the increased head. There may be enough hydraulic head to force the water to the surface in what is called a flowing artesian well, or to cause ground-water flow across aquitards (confining units) (Figure 6).

Ground-water Movement

The water table height in confined aquifers is actually a potential height to which the ground water would rise in a well or pit if not confined by the overlying confining unit, such as water freed by drilling a well. This potential height (pressure) exists everywhere in the confined aquifer and is known as the potentiometric surface. Wells show hydraulic pressure (known as head) much like a giant pressure gage. This hydraulic pressure, due to gravity acting on water in higher areas of the aquifer, is responsible for the movement of ground water; it is the driving force.

As stated before, all geologic materials pose some impediment to the flow of water through them, due to frictional fluid forces and convoluted flow paths around grains and through pores. If flow were very fast, the mounding effects and variations in the potentiometric surface would not be seen. Fractures in rocks can act as conduits for ground-water flow, and this effect can be very important to overall flow patterns, offering relatively unimpeded flow paths. However, this flow is very complex.

Advection

Advection is the hydraulic principle governing ground-water flow. Advective flow is the product of several parameters, which are expressed as Darcy's law, $Q = KIA$. It states that the flow rate through any porous medium is 1) proportional to the pressure driving the flow (head), 2) inversely proportional to the length of the flow path, and 3) affected by the hydraulic conductivity of the porous medium (geologic material). Exercise A1 deals with practical application of Darcy's Law describing flow per unit area.

Geometric Changes to the Potentiometric Surface

When a well is drilled into an aquifer, a casing pipe is installed to keep equipment from being damaged and to allow pressure or suction to be applied to the area near the bottom of the well. The casing has holes in it in this section. This is called the screen, and this area provides access to the geologic materials (aquifer) outside of the well in a controlled manner. A water well is drilled until it has penetrated the water table or potentiometric surface of the particular aquifer desired. Water is withdrawn by pumping and water from surrounding parts of

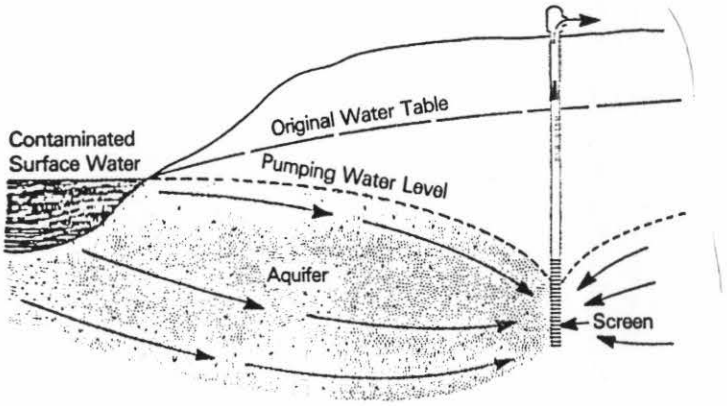


Figure 5: Diagram showing how contaminated water from a surface body can be induced to flow into ground water, and subsequently the withdrawal well, by pumping (U.S. EPA, 1987, from Miller, 1980).

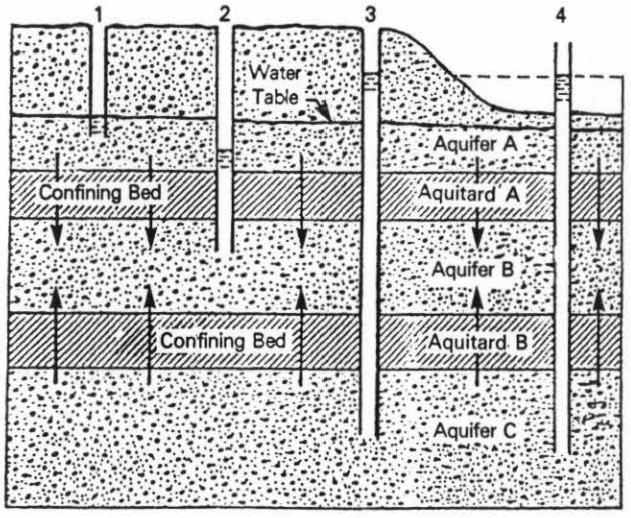


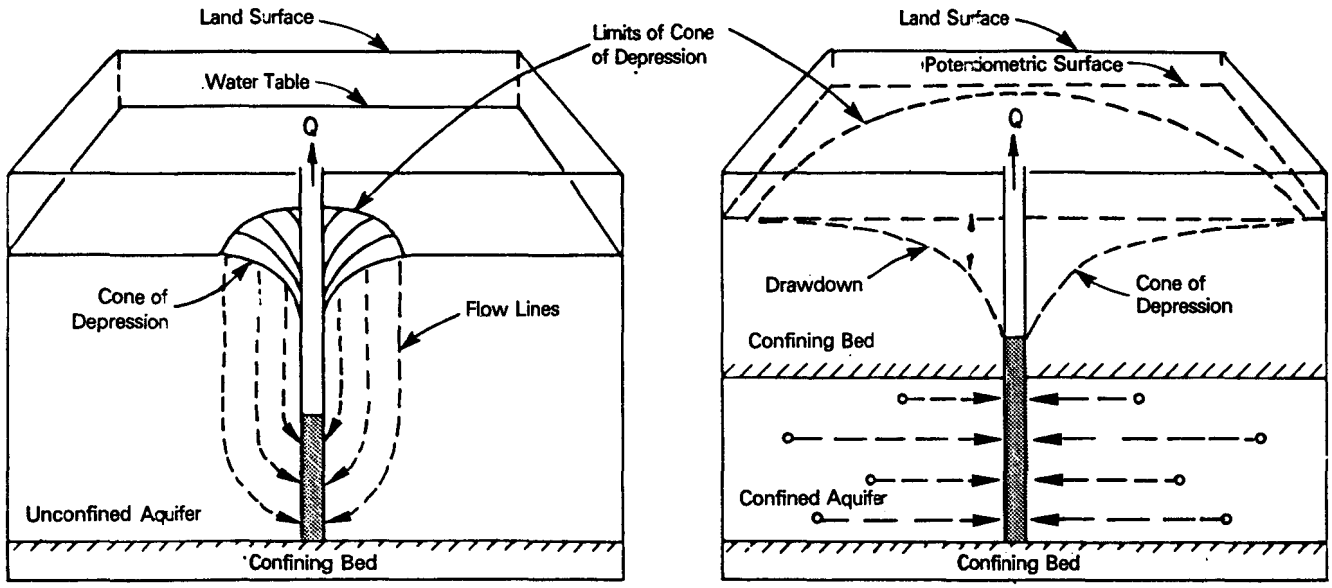
Figure 6: Aquifer A is unconfined and aquifers B and C are confined, but may leak through confining units to recharge adjacent water-bearing zones (U.S. EPA, 1987).

the aquifer flows towards the well to replace that which is pumped out. Wells that remove water from an aquifer (pumping or withdrawal wells) modify the potentiometric surface and affect ground-water flow patterns. The surrounding flow is necessarily modified because water now flows towards the well to replace that which is pumped out. What is known as a cone of depression forms around the well in the potentiometric surface (or water table) (Figure 7).

The size and shape of the cone of depression depends upon the withdrawal rate, the hydraulic conductivity of the surrounding rock or sediments, and the period of withdrawal. The hydraulic head is lowered locally for withdrawal wells and equipotential lines in the vicinity show a characteristic series of concentric contours indicating the withdrawal area. Flow paths or flow lines are lines drawn on maps and cross sections depicting the direction of flow that individual water "particles" travel underground. Figure 8 shows typical flow paths in the vicinity of an extraction well. Flow paths, which necessarily cross equipotential lines at right angles, are diverted towards the withdrawal area. The situation is different for wells adding fluid to the subsurface. An injection well is one in which water is introduced under some type of pressure, by means of a well casing with either the water level maintained above the potentiometric surface, or by active pumping. Here the effect on the potentiometric surface is opposite: the potentiometric surface is raised above the surrounding areas. This is a case of highly localized recharge, and water immediately begins to flow away from this area due to the new hydraulic gradient. Of course, the flow rate and direction are affected by the hydraulic conductivity of the aquifer unit being injected and by any preferential, anisotropic effects of the sediments or rock. This ability to manipulate the potentiometric surface and subsequent subsurface flow using both withdrawal and injection wells represents a major tool to be used in the control and cleanup of subsurface contamination.

Geologic Information

Information on geologic conditions in the subsurface is presented in a variety of ways, some of which is used in the educational units developed in this thesis. When drilling a well, the drill bit passes down through successive layers of soil and rock. A detailed record of the types and thicknesses of sediments or rocks encountered is made at that time. This record, a well log, can be augmented by putting a great variety of instrumentation down the borehole during or after drilling. Special devices can be used to retrieve samples of the geologic materials at various levels or any of fluids encountered. These samples can be very important in quantifying the hydrogeologic properties of the area under study. They provide hard data for the operation and checking of theoretical and laboratory models of ground-water and contaminant flow. The data gathered can be used to create a cross section of the area. Cross sections show an elevation (sideways) view of the layers and underground structure of an area. Some of the previous figures have been cross sections. They show the subsurface in a sideways view, similar to a cake slice.



The cone of depression surrounding a pumping well in an unconfined aquifer is relatively small compared to that in a confined system.

Figure 7: Cones of depression in a) confined and b) unconfined aquifers (U.S. EPA, 1987, from Heath, 1983).

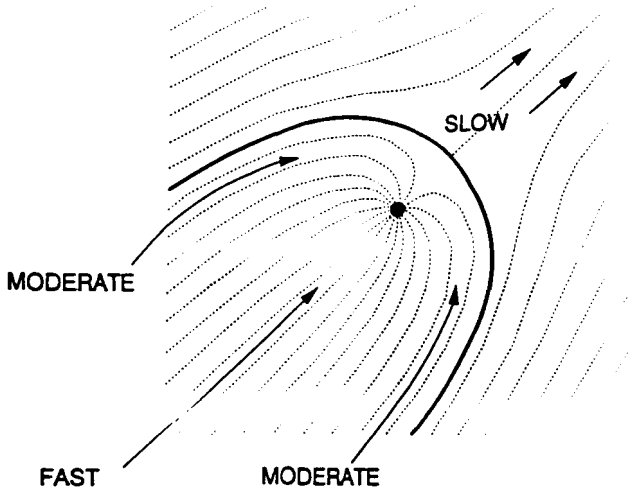


Figure 8: Flow line generated by an extraction well (U.S. EPA, 1989).

Chapter 3 - Unit B: Transport and Fate of Ground-Water Contaminants

Introduction

This unit investigates the occurrence, types, and sources of contaminants. Transport of contaminant in the subsurface and dispersion and diffusion phenomena are also discussed. Finally, contaminant isolation and remediation strategies are introduced. The exercises for Unit B are located in Appendix II.

Types of Contaminants

Virtually any toxic or usage-limiting chemical or compound, either created by humans or occurring in the natural environment, has the potential to contaminate ground water, not just those caused by such site-specific incidents as leachates from landfills or surface spills. Contaminants cause water to become "polluted" when the contaminant concentration increases above a certain level (a quality standard set by agencies and/or law). Human activities can cause the migration of natural contaminants (such as highly mineralized or saline ground water) into previously uncontaminated aquifers.

Contaminants are of three basic types: physical, chemical, and biological. Physical contaminants (those whose chemical interactions are not of primary importance) include radioactive particles (isotopes) and asbestos. Metal ions, the most dangerous being the more toxic "heavy metals," are included in the second basic grouping of contaminants: chemical. This is the most diverse and prevalent contaminant group. Industry brings new chemicals into widespread use every year, so the list of potential contaminants continually grows and evolves. Chemical contaminants can be categorized further: metal ions (mentioned previously), acids and alkaline substances, ionic compounds, and organic chemicals, including petroleum-based fuels. This sub-group, the organics, is very complex and diverse. Included here, besides fuels and oils, are organic solvents (eg. benzene), pesticides and fertilizers (nitrates), chlorinated solvents and compounds (including PCBs), and complex compounds such as dioxins and furans. The last basic type of contaminant is biological: bacteria and viruses that survive in the subsurface and that can cause harm to humans.

Contaminants can be in their pure form (free-product phase) or dissolved or entrained into ground water (U.S. EPA 1987)

Nonaqueous-Phase Liquids

A special group of organic chemicals exists: nonaqueous-phase liquids (NAPLs). These are hydrocarbon contaminants which do not mix with water, but yet are mobile in the subsurface. These compounds have recently been recognized as a major problem in the effort to clean and

protect many aquifers (U.S. EPA, 1991). Complicating the problem is the fact that soluble portions of NAPLs dissolve into ground water, contaminating it. However, this diffusive process takes time and much of the liquid remains in a separate phase having very different properties from water. In this manner it acts as a reservoir for continued contamination of associated ground-water. NAPLs that are less dense than water, light nonaqueous-phase liquids (LNAPLs), will float on top of the water table. Dense nonaqueous-phase liquids (DNAPLs) are more dense than water and will penetrate and sink into the water table if sufficient quantities accumulate. NAPLs present serious problems for both the detection of contaminants and cleanup (remediation) of an aquifer and/or the unsaturated zone above an aquifer.

DNAPLs present an especially tough problem that is now being recognized at many contaminant sites that have been undergoing cleanup for some time. DNAPLs can become immobile in the subsurface, yet continue to contaminate ground water for centuries (U.S. EPA, 1991). Immobilization occurs by partitioning onto organic solvent or materials. Initial efforts at many sites were not designed to detect DNAPL contaminants, yet they are often present and remain the source of continuing ground-water contamination (U.S. EPA, 1991). DNAPL movement in the subsurface is very much controlled by forces different from those controlling dissolved-phase contaminants and ground water. Capillary forces and the distribution of these forces in geologic materials exert a far greater effect on them. Even marginal remediation of DNAPLs requires more detailed information on these properties than for other contaminant materials. However there is a risk that DNAPLs will spread contamination further during site evaluation (drilling and sampling). No proven technologies able to completely clean up aquifers contaminated with DNAPLs completely, and containment is the primary, realistic goal in these aquifers (U.S. EPA, 1991).

Sources of ground-water contamination

Contaminants can be released into the environment by design, through ignorance or neglect, or by accident. Figure 9 shows common sources of ground-water contamination. These can be studied in a framework of 6 categories as detailed in Table 1.

Contaminant Transport

Flow of many ground-water contaminants is controlled predominantly by hydraulic pressure and by density. Mixing characteristics of contaminants in water and wetting/capillary interactions with geologic materials are also important. Permeability and the wetness of those geologic materials also contribute to the net movement of a contaminant. Capillary action and gravity draw a spilled contaminant into a soil where the contaminant begins to fill soil pores. Some is trapped as the contaminant moves downward, displacing soil gas (liquids are denser). If

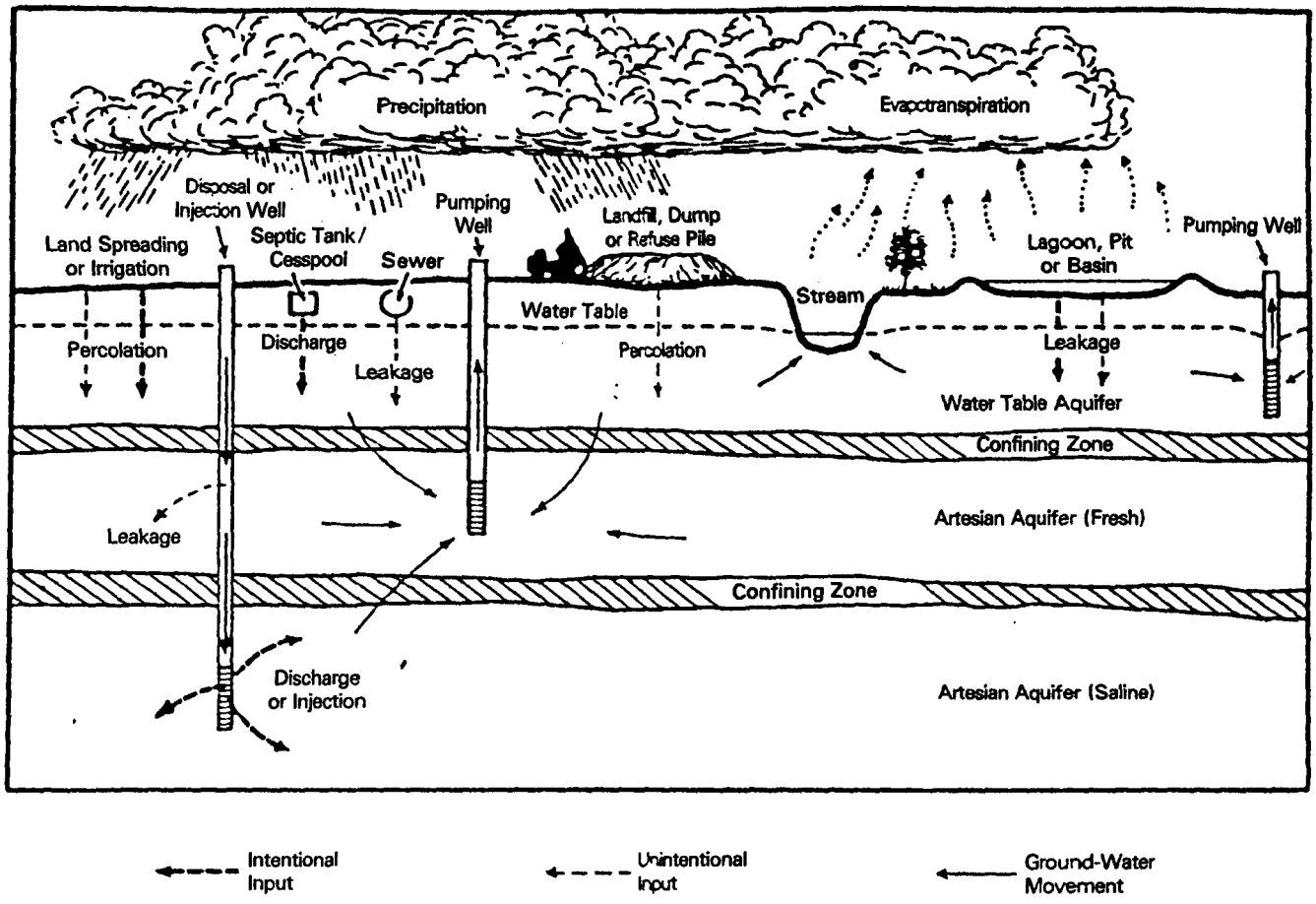


Figure 9: Methods of contaminant release. Dotted arrows show unintentional movement of contaminants. Heavy dashed arrow shows intentional input to the environment. Solid arrows show general ground-water movement. (U.S. EPA, 1987, from Geraghty and Miller, 1985).

Table 1: Sources of ground-water contamination. (U.S. EPA, 1987, from OTA, 1984).

Category I—Sources designed to discharge substances

Subsurface percolation (e.g., septic tanks and cesspools)
Injection Wells
  Hazardous waste
  Non-hazardous waste (e.g., brine disposal and drainage)
  Non-waste (e.g., enhanced recovery, artificial recharge, solution mining, and in-situ mining)
Land application
  Wastewater (e.g., spray irrigation)
  Wastewater byproducts (e.g., sludge)
  Hazardous waste
  Non-hazardous waste

Category II—Sources designed to store, treat, and/or dispose of substances; discharge through unplanned release

Landfills
  Industrial hazardous waste
  Industrial non-hazardous waste
  Municipal sanitary
Open dumps, including illegal dumping (waste)
Residential (or local) disposal (waste)
Surface impoundments
  Hazardous waste
  Non-hazardous waste
Waste tailings
Waste piles
  Hazardous waste
  Non-hazardous waste
Materials stockpiles (non-waste)
Graveyards
Animal burial
Aboveground storage tanks
  Hazardous waste
  Non-hazardous waste
  Non-waste
Underground storage tanks
  Hazardous waste
  Non-hazardous waste
  Non-waste
Containers
  Hazardous waste
  Non-hazardous waste
  Non-waste
Open burning and detonation sites
Radioactive disposal sites

Category III—Sources designed to retain substances during transport or transmission

Pipelines
  Hazardous waste
  Non-hazardous waste
  Non-waste
Materials transport and transfer operations
  Hazardous waste
  Non-hazardous waste
  Non-waste

Category IV—Sources discharging substances as consequence of other planned activities

Irrigation practices (e.g., return flow)
Pesticide applications
Fertilizer applications
Animal feeding operations
De-icing salts applications
Urban ruhnoff
Percolation of atmospheric pollutants
Mining and mine drainage
  Surface mine-related
  Underground mine-related

Category V—Sources providing conduit or inducing discharge through altered flow patterns

Production wells
  Oil (and gas) wells
  Geothermal and heat recovery wells
  Water supply wells
Other wells (non-waste)
  Monitoring wells
  Exploration wells
Construction excavation

Category VI—Naturally occurring sources whose discharge is created and/or exacerbated by human activity

Groundwater—surface water interactions
Natural leaching
Salt-water intrusion/brackish water upconing (or intrusion and other poor-quality natural water)

enough compound was released, it will reach the water table. Here soluble compounds begin to dissolve into the ground water. Less soluble compounds either spread out over the surface of the water table (if they float on water) or start to sink and penetrate the water table. If smaller amounts of contaminant is released, or the water table is far below the ground surface, the contaminant may not reach the water table. This is due to sorption onto and coating of the unsaturated-zone materials and trapping of some portion in soil pores. These processes can reduce the amount of contaminant in the mass as it seeps downward.

Movement of Contaminant Plumes

Three general processes act on chemical contaminants in ground water. They are advection, dispersion, and retardation. Advection was discussed in Unit A when basic ground-water flow was described, along with Darcy's Law. Dispersion is the spreading out of a contaminant plume due to irregular flow and mixing. Retardation is the slowing of a contaminant plume by any one or more mechanisms.

Advection of Contaminant Plumes

Advection is the term used to describe both ground-water movement and the transport of a nonreactive, conservative compound at the average velocity of surrounding ground-water flow. One method used to measure velocity (and also direction) is to introduce a tracer of some sort into a well and measure how fast (and perhaps where) it moves. There are many types of tracers (including contaminants themselves) and many tracing methods. Simple methods include measuring how fast a tracer is carried out of a well by ground water flowing by and through the well. Or, a series of surrounding wells can be drilled into the same geologic units and then measured by the time it takes for the tracer to travel to another well. This method indicates the direction that ground water is flowing.

Figure 10 shows a contaminant plume from a leaking waste disposal lagoon being moved along with the regional flow of ground water. The equipotential lines and flow path arrows are shown. Note that the lagoon contributes to the aquifer flow and that the river gains water from the aquifer, which is contaminated in this case.

Dispersion of Contaminant Plumes

Dispersion in hydrogeological terms is the group of forces acting to dissipate, or to thin out a contaminant mass in the subsurface. Dispersion occurs in all directions and can be affected by the properties of the geological material. It is caused primarily by the differences in velocity found in a pore channel. The same effect is seen in a pipe transporting fluid, such as a water or steam pipe. If the flow is measured at various points across a cross section of the pipe,

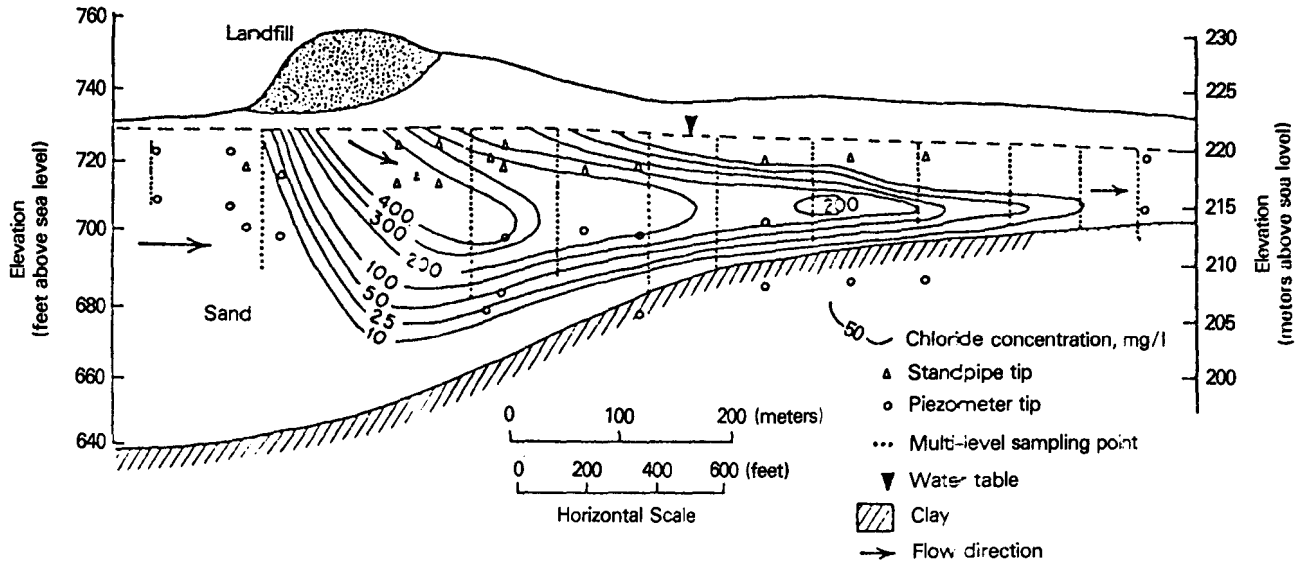


Figure 10: Plume of leachate migrating from a sanitary landfill on a sandy aquifer showing highest contaminant concentration at the center of the plume (U.S. EPA, 1987, from Freeze and Cherry, 1979).

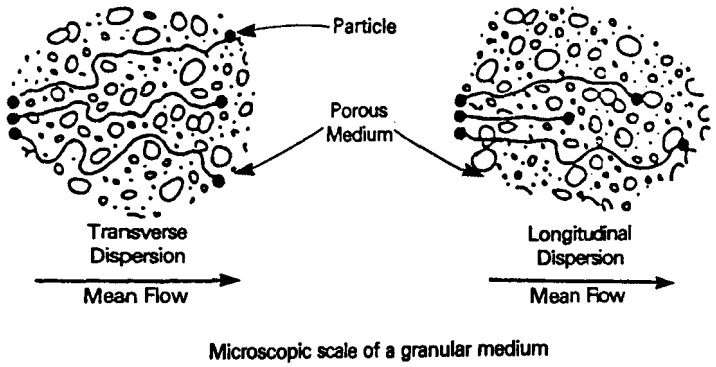


Figure 11: Diagram of transverse and longitudinal dispersion at the microscopic level particle paths in matrix showing longitudinal & transverse diffusion plume (U.S. EPA, 1987, adapted from Freeze and Cherry, 1979).

flow is found fastest at the center and slower closer to the pipe wall (side of the pipe). This is due to drag effects between the pipe and fluid. The same effect occurs in pores in geological materials, which can have any number of shapes.

The slowing of only part of the flow relative to another creates no effect when the transported fluid is just ground water. However, when a contaminant is mixed with the water, the net effect is dispersion. Some of the contaminant gets positioned in the flow adjacent to a pore wall, while the now-reduced amount forges ahead with the fastest water flow. This process tends to spread the plume out along the axis of general flow--longitudinal dispersion (Figure 11).

Contaminant plumes disperse in a direction transverse to flow by several mechanisms. The most important is caused by the convoluted flow path taken by all fluids around the grains of the material through which it is flowing. These pathways as a whole add up to the general flow direction. But some water and contaminant "particles" take very tortuous flow paths. The velocity of some portions of the flow is slower than others, and the net result of this is the same: dispersion of the contaminant mass.

Dispersion of contaminants must always be considered along with advection when trying to determine the transport of a plume of contaminants. Geologic materials (the soil and broken rock near the surface, as well as bedrock and aquifer materials) contain pores of a variety of shapes, sizes, and relative position. Pores that are not round can be oriented in a preferential direction, depending on the geological forces that emplaced the materials.

Another method of dispersion is diffusion, the tendency for concentrations of compounds in solution to spread out and equalize the overall concentration. All methods of dispersion tend to reduce the concentration of an advecting plume. The effect at a monitoring well downgradient from the source is not one of a massive increase in contaminant concentration from zero to the maximum as the plume front arrives, but instead is a curve increasing to a maximum. This curve is called the breakthrough curve and is illustrated in Figures 12 and 13 (a and b). These are plots of contaminant concentration at increasing distances from the source. The second set of graphs shows a plot of a one-time release (a slug). Two different time periods are shown illustrating the cumulative effect of dispersion over longer and longer distances. Note the typical bell shaped curve. Refer to Figures 14 and 15, which illustrate contaminant fronts unmodified by dispersion. Some typical actual plume shapes are shown in Figure 16 (a and b), and in Figure 17.

The movement of both ground water and contaminants is controlled by the same factors: gravity, the permeability and wetness of the geologic materials they come into contact with, and how miscible (soluble) the contaminants (or components of a complex contaminant, eg. gasoline) are in ground water. Any liquid has a density greater than air and will displace the gas component in the unsaturated zone.

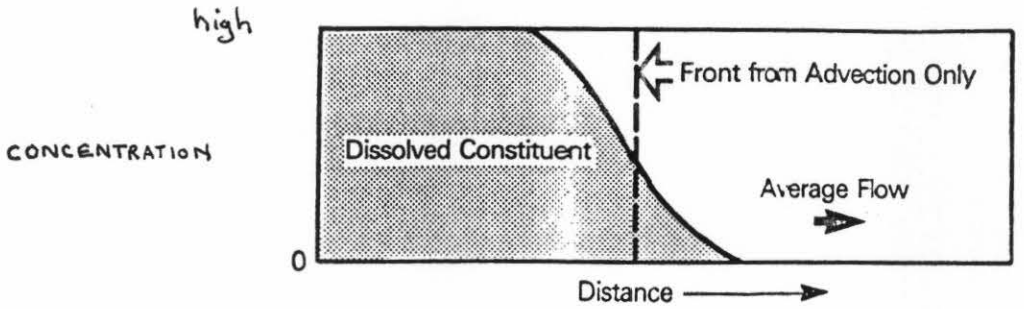


Figure 12: Plot of contaminant concentration versus distance from contaminant source showing the movement of a concentration front by advection and modified by dispersion (from U.S. EPA, 1987).

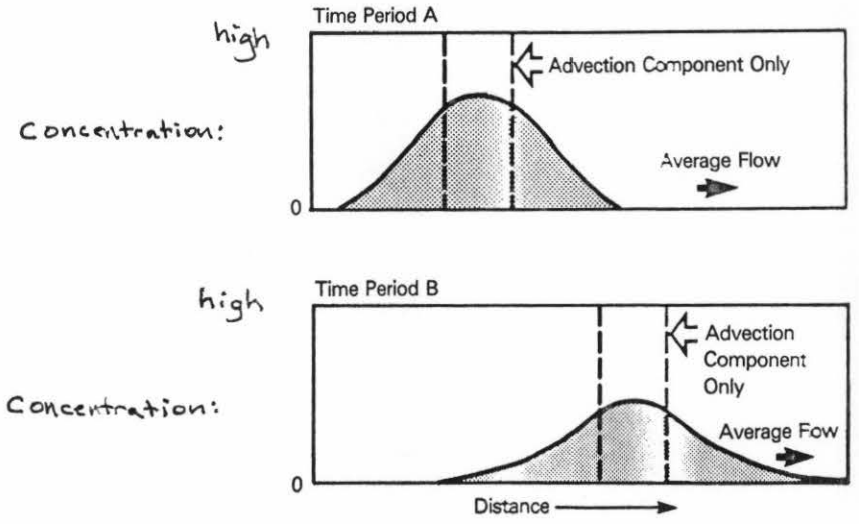


Figure 13: Plots of contaminant concentration versus distance from contaminant source for a dissolved contaminant slug showing movement by advection and the change in plume shape due to dispersion. Note that dispersion increases over time and therefore distance from the contaminant source (from U.S. EPA, 1987).

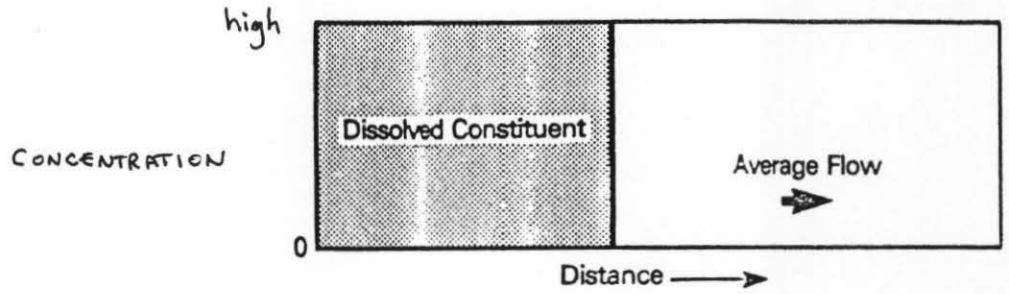


Figure 14: Plot of contaminant concentration versus distance from contaminant source showing the movement of a concentration front by advection only (from U.S. EPA, 1987).

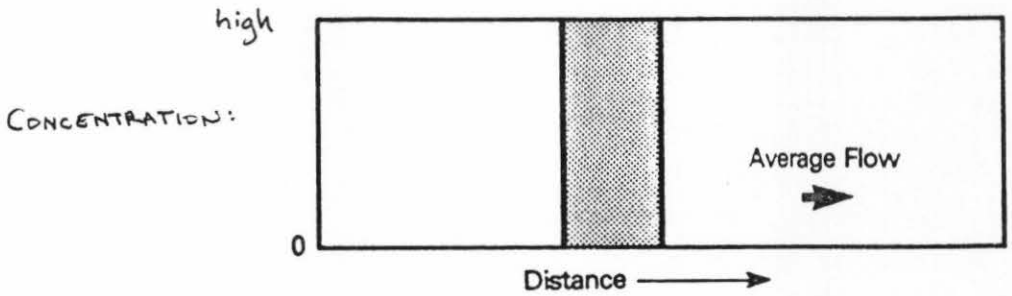


Figure 15: Plot of contaminant concentration versus distance from contaminant source for a dissolved contaminant slug showing movement by advection only(from U.S. EPA, 1987).

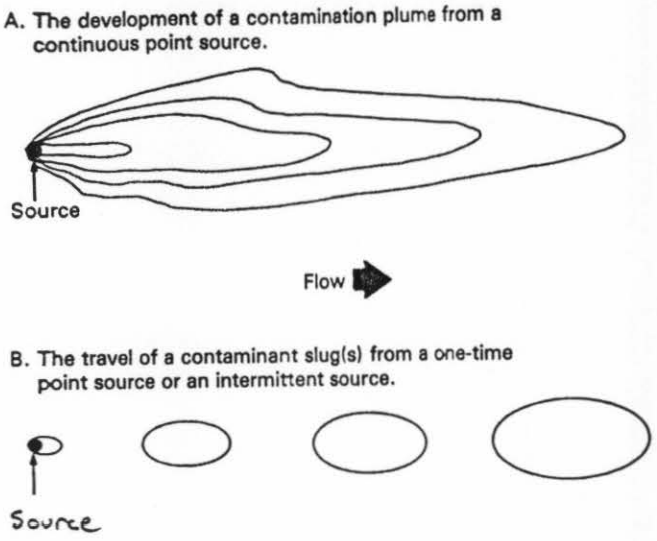


Figure 16: Effects of continuous and intermittent sources on plume shapes as affected by dispersion (U.S. EPA, 1987).

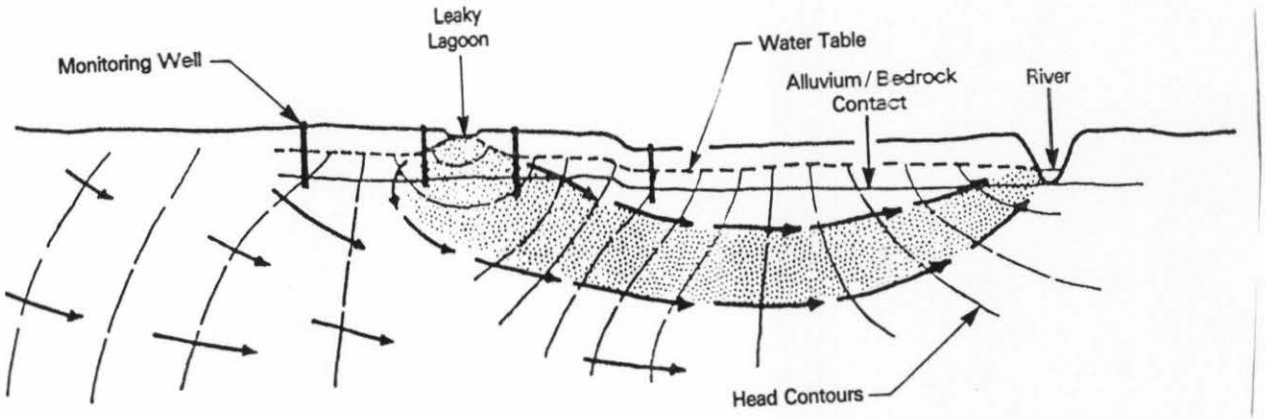


Figure 17: Effect of leakage from a lagoon on a regional flow pattern; typical plume migration path is shown (U.S. EPA, 1987, from Geraghty and Miller, 1985).

An initial spill of a hydrocarbon is wicked into the soil by capillary action and gravity. Air must be displaced until the water table is reached. Highly miscible materials dissolve into the ground water right away, while less miscible materials float and spread laterally or tend to penetrate the water table. In all cases the ground-water flow will tend to entrain the contaminant (through hydrodynamic and viscous forces) and move it downstream.

Retardation

Movement of contaminants in the subsurface can be slowed down by a number of chemical and physical processes. They retard or delay the migration, sometimes substantially, relative to surrounding water underflow. These processes can be broken down into four categories: dilution, filtration, chemical reactions, and transformation. The first category includes dispersion, which can break up a slug of contaminant and cause intermixing with water. The reduced concentration may be below the contamination-problem threshold at a point of usage for the aquifer water. Diffusion gradients, a type of dispersion, are reduced when contamination is diluted. Filtration is relatively simple in operation: contaminants become trapped in smaller pore spaces. The latter are the same flow paths that allow advection and thus may clog up over time, reducing flow.

Ion exchange, the exchange of ions of a contaminant/ground-water solution with geological materials present in the subsurface, is a very important retardation process. Ion exchange can remove contaminant ions from the flow, only to release them later if chemical equilibrium conditions change. This is usually controlled by changes in pH (U.S.. EPA, 1987). The geological materials present a limited number of exchange "sites" on molecules, and these can be exceeded over time by continuously refreshed leachate. When the capacity is exceeded, contaminant ions begin to move freely.

Transformation mechanisms of retardation include volatilization, where parts of the contaminant change from the liquid to the gaseous phase. This can reduce the viscosity of a contaminant also. Contaminants can also be affected by microbal activity in the subsurface, knowledge of which has only recently come to light (U.S. EPA, 1987). Biotransformation can degrade a contaminant to another compound, with a different mobility and characteristics.

The effects of retardation on a complex contaminant plume leaching from under a waste pile is illustrated in Figure 18. Monitoring wells are shown placed at increasing distances form the pile, down into the plume area. The sketch is of conditions at one particular moment in time. Compounds with higher retardation rates for the specific conditions under the site have not traveled as far as those with lower retardation rates.

Contaminant Isolation and Remediation Strategies

The ideal goal would be to clean up every contaminant site to the degree that it was indistinguishable from a virgin site. No evidence of contamination would then be detectable through investigation or through effects on the environment or humans. This is impossible, not only because of technical limitations, but also due to limited fiscal resources. Often a site must be viewed in the continuum of what it was used for, how much income was generated during its use, and what the cost benefits of varying degrees of remediation versus the (and aquifer's) future value (a broad term here) of the site and aquifer will be. Parties found legally responsible have finite resources and the government makes up the difference when the cost of dealing with the problem exceed those resources. The government and society also have finite resources, generated by taxes and loans to be repaid with future taxes.

The realistic goal is to contain (isolate) and/or treat (remediate) contaminated ground water, and to clean (or partially clean) contaminated aquifers deemed of high economic value. Ground water and contaminants can be extracted and treated by physical, chemical, or biological methods on the surface or in-situ (in place underground) by chemical or microbal methods. This section provides an overview of all processes, with a more detailed analysis of physical-containment and remediation techniques. The source materials used for this thesis emphasize hydrocarbon contaminants, and that bias is reflected herein.

Hydrocarbon Contaminants: Physical Processes

An obvious first step towards remediation, after site characterization and study, is to prevent or slow the spread of contamination. This can be viewed as a step-by-step process, starting at the mechanism for contaminant release. If a leak is responsible for the release, it is stopped by repair or transfer of materials. Leaking barrels are removed and leaking lagoons pumped out. If significant amounts of contaminant are present in near-surface soils and these are infiltrating the ground, they would also be removed. Another approach is to prevent further infiltration into the subsurface by controlling infiltration of surface water. This is done via impermeable barriers on the surface, planting vegetation with high evapotranspiration rates, and controlling surface flow on the ground and into bodies of water, through contouring the surface (grading) or digging surface collection trench systems.

Once the contaminant has migrated into the subsurface, the strategy of containment is employed. The first type of containment consists of installing an underground barrier highly impermeable to the contaminant plume, a type of curtain. These barriers, of clay, metal, or polymers, ideally block any migration route in the subsurface. Sometimes these barriers can be "locked into" an impermeable layer below the site, preventing flow underneath them. If that option is not available, due to deep or nonexistent boundary layers, these barriers, may still be of

use to prevent migration of contaminants and vapors in the near surface. Subsurface barriers can be thought of as hydrostatic controls, as compared to active pumping (hydrodynamic) controls. Barriers can be used along with hydrodynamic controls to make the latter more effective.

The above options of removal, surface infiltration control, and barriers all have limitations, such as high cost or unavailable materials, lack of acceptable dumps (or transport to them), and the inability to verify the integrity of subsurface barriers.

The last method of containment is through hydrodynamic control of the contaminant plume relative to the pre-existing site flow conditions. The goal is to isolate the plume from other uncontaminated waters or flow, and to prevent further movement of the pollutant(s) through the subsurface. A series of injection wells up gradient (upstream) from the plume inject uncontaminated water at a rate high enough to overcome the ground-water flow (hydraulic) gradient into the zone of contamination. The water to be injected is withdrawn from areas adjacent to the plume, but far enough away so that contaminated water is not drawn into these wells. This approach requires thorough knowledge of flow parameters in all surrounding materials, and plume location and extent; it also requires careful operation of the system. This is an active system that requires continuous monitoring and power input for as long as the plume remains.

Withdrawal and Treatment

This technique can involve withdrawal wells, or both injection and withdrawal wells (or buried trenches as in Figure 19. The latter approach could be considered an elaboration of hydrodynamic containment. In simple withdrawal, contaminated water (or pure contaminant) is pumped to the surface for treatment. Surface treatment options are quite varied and are not discussed in this work.

In injection/withdrawal systems, wells down gradient from the contaminant plume withdraw water where it is delivered to some type of treatment system which removes contaminants. This water is injected through wells up gradient of the plume, accomplishing two tasks. The water is injected at a rate high enough to overcome the hydraulic gradient into the zone of contamination, forcing the pre-existing flow around the plume. Much of the injected water flows into the plume area and begins flushing the plume from aquifer materials, beginning the remediation of contamination. The definition of withdrawal and treatment technique could also be applied to the extraction of soil contaminant gases.

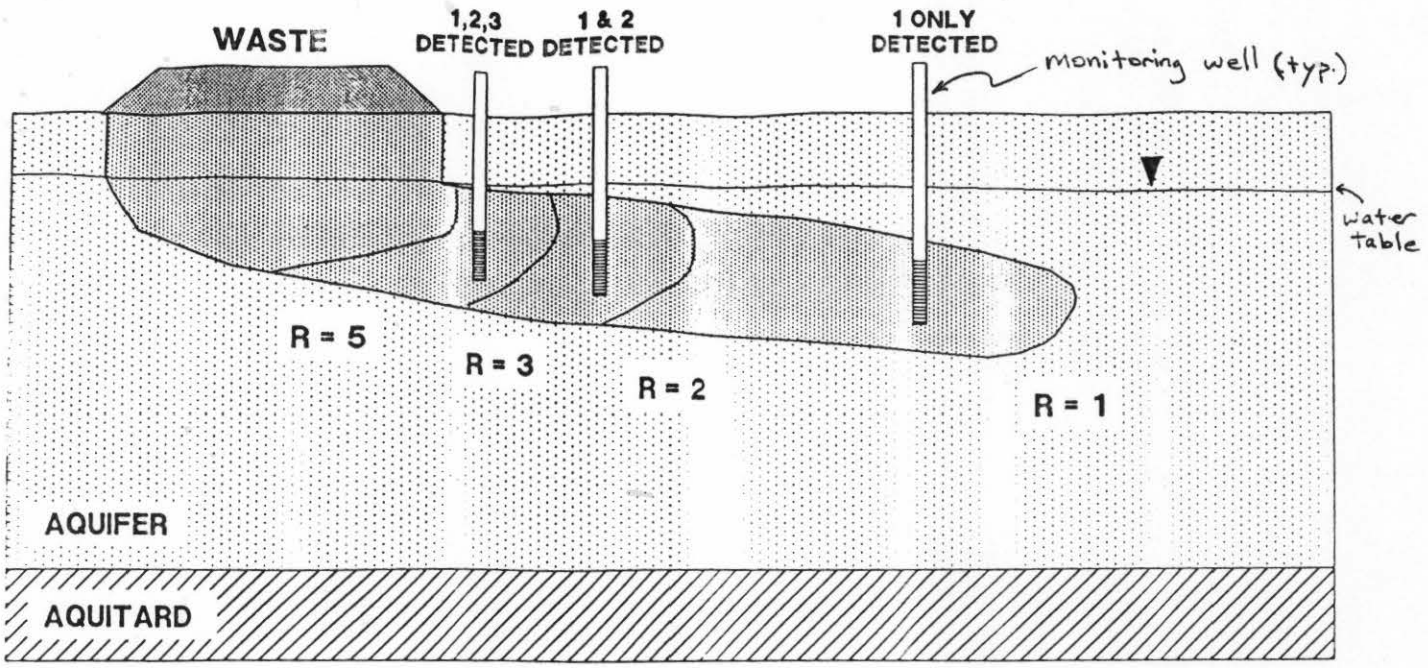


Figure 18: Cross section of typical waste pile showing distribution of contaminants with different retardation factors in the aquifer materials. The contaminant that has spread the most is the least affected by any retardation (from U.S. EPA, 1989).

DNAPLs present special problems to remediation and special dangers to the environment when present. Physical removal via pumping, trenches, vacuum extraction of soil gas, soil flushing, physical barriers, and the use of hydrodynamic controls is used to control DNAPL contaminants.

In some cases the contamination of an aquifer or at a site may be so widespread or so difficult to reach and remove that cleanup is not possible and containment is the only approach. Even containment cannot be assured by using subsurface barriers and hydrodynamic controls in other areas. These areas are affected by widespread contamination, fractured bedrock, or regional underground stream systems (U.S. EPA, 1989). In these cases the entire aquifer is sometimes made off-limits to withdrawal by pumping through code restrictions on water wells. Affected peoples and businesses are provided with alternate sources, through extended water supply piping systems. The factors that are considered when making the judgment for either containment alone, or including cleanup, have been discussed at the beginning of this section.

Soluble Contaminants

Soluble contaminants dissolve in ground water and do not become immobilized as readily as many hydrocarbon contaminants. Common methods of remediation are the same as those utilized to treat ground water contaminated with the soluble components of hydrocarbons, which are covered in the previous section. Aquifer flushing is often used, with the chemistry of the flushing water adjusted to facilitate mobilization of all the pollutant.

Summary

The U.S. EPA booklets and manuals provide a good starting place for the generation of educational materials regarding hydrologic principles and the transport and fate of subsurface contaminants. These manuals contain materials for which additional exercises could be generated. For example, an exercise combining equipotential maps and flow paths could be integrated into a scenario where changes are made to the potentiometric surface and contaminant flow paths are modified. The source materials provide numerous site examples which could be reworked into additional exercises.

Appendix I

Exercises for Unit A

UNIT A

EXERCISE A1: Ground-water Flow Rates

Introduction

In this exercise you will examine how hydraulic head and ground-water flow are interrelated and will calculate flow through a confined aquifer of simple geometry. The Darcy flow equations govern flow in this instance. Part A of Exercise A1 presents the concepts; Part B is the exercise containing actual calculations.

Supplies and Equipment Required

Calculator, notebook paper

Objectives

Review the relationship between hydraulic head and flow direction in Unit A. Calculate the flow through a confined aquifer using data from two observation wells.

Tasks

Part A:

Darcy's Law is the basic expression used to describe fluid flow in aquifers. It can be modified in a number of ways to account for different flow situations, but in its basic form (shown below) it calculates the quantity of fluid flow per unit area (across the direction of flow).

Darcy's Law: $Q = KIA$ [flow per unit area]

Where Q = quantity of flow per unit time
K = hydraulic conductivity of the aquifer, in gal/d/ft^2
I = hydraulic gradient (hydraulic head), in feet per foot (ft/ft)
A = cross-sectional area through which the flow occurs

The equation takes into account the resistance that the aquifer poses to flow, the pressure on the fluid (hydraulic head), and over how much area this hydraulic gradient can act. An example of how hydraulic head affects the fluid flow direction is shown in the 3 schematics in Figure 20. They represent sand filled tubes: confined aquifers with a cross-sectional area of A. The ends are constructed so that water can be forced in one end and the resulting flow amount measured at the other end. The tubes have a pair of flexible hoses connected to the sides, one near each end, L feet apart. These tube will be used to measure the hydraulic head at the points where they connect to the aquifer tube, much like observation wells in a real aquifer.

Figure 20a shows a tube in a horizontal position and a quantity of fluid per unit time is made to enter the tube. The water can be considered incompressible and flows through the sand and out the other end. The water level rises in the hoses in response to the force being applied to the water to push it through the sand. Energy is expended moving the fluid through the sand and this shows up as a lower hydraulic head measured in the downstream measuring hose. The difference in head (H) along the flow path length (l) is the hydraulic gradient and is expressed as H/L. If the flow (Q) and area (A) are constant, but a different aquifer material is present, say with a lower hydraulic conductivity, the head loss will be greater. Flow is in the direction of decreasing head.

Figure 20b shows tubes oriented vertically. In one case, water is being forced up through the tube from below. The hydraulic head will always decrease in the direction of flow, and the measuring hose upstream (to the flow direction) show a higher hydraulic head. In the other situation, flow is seen form the top down, and the hydraulic heads in the measuring hoses are reversed. The measuring hoses are like a pair of wells in the field, one drilled to a shallow depth and the other drilled deeper. This scenario is illustrated in Figure 20c, which shows the water levels in 3 sets of wells located in a recharge area, an area of horizontal flow, and an area of discharge.

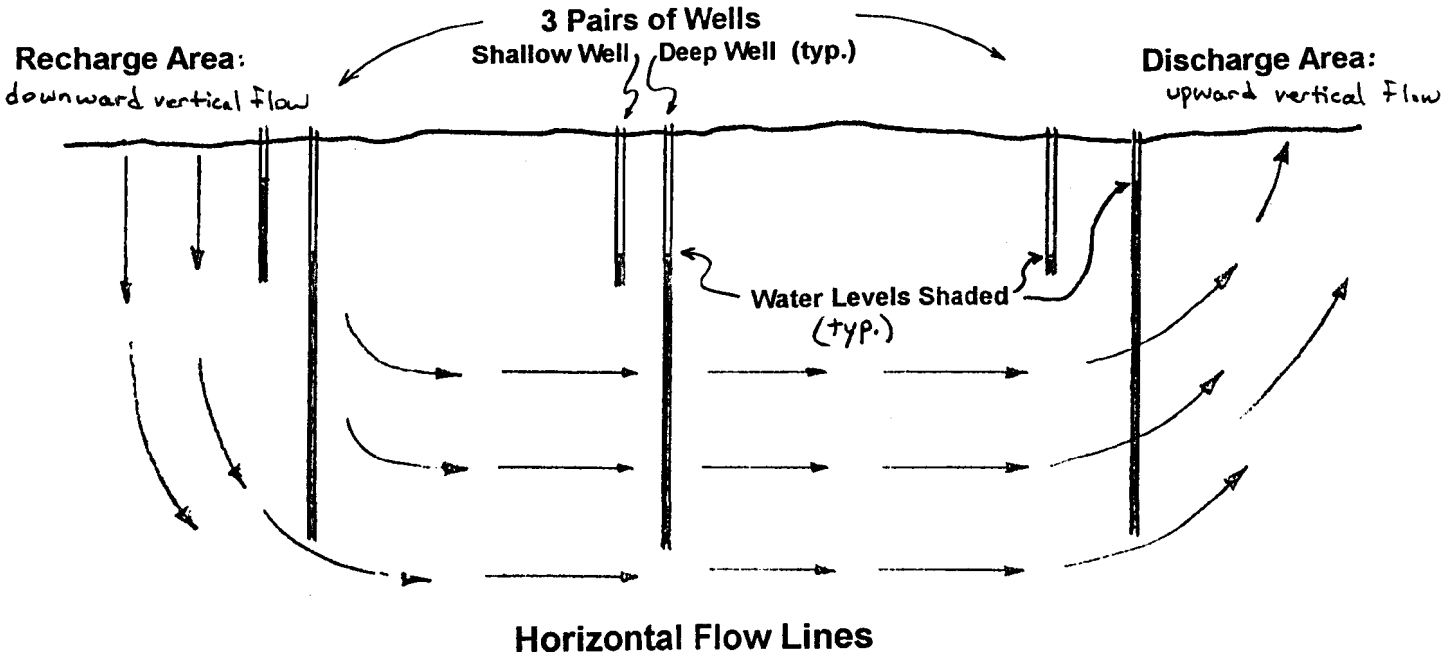
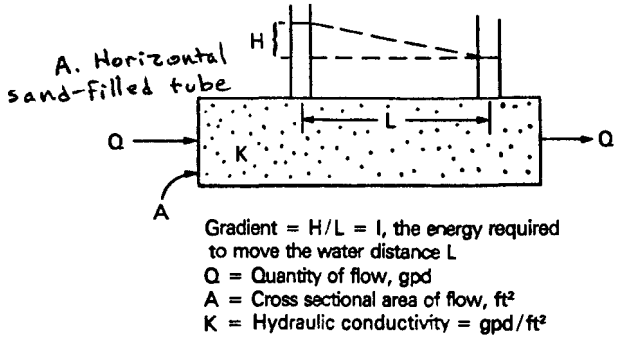
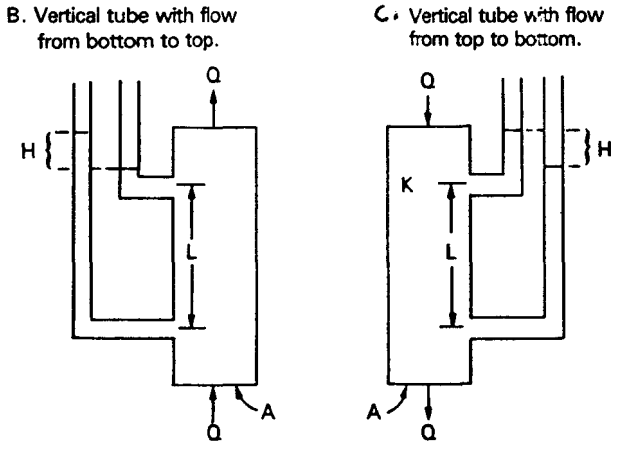


Figure 19: Cross section diagram of hypothetical regional ground-water flow. Water levels of pairs of wells illustrate the hydraulic head driving the flow. (from U.S. EPA, 1987).





Figures 20a, b, & c: Sand-filled tubes illustrate Darcy's Law and the relationship of hydraulic gradient to flow direction. (from U.S. EPA, 1989).

Part B:

In the following example (adapted from U.S. EPA, 1987) you will use Darcy's Law to calculate the underflow (underground flow) in a confined sand aquifer. Parts of the cross-section of a sediment-filled valley are shown in Figure 21 where they intersect with two observation wells. They are located one mile (5,280 ft.) apart, one directly up-flow from the other. The aquifer is confined by glacial till with a surface that is essentially flat, as are all bedding planes and unit-to-unit boundaries. The observation well logs (prepared when the wells were drilled) show the till to be 40 feet thick, and the sand aquifer to extend from the base of the till to a depth of 75 feet where it overlies the essentially impermeable bedrock shale. The valley has been cut into this shale bedrock and the flood plain sediments are approximately 1500 feet wide in this area. One observation well shows the potentiometric surface 15 feet below the surface, and the other shows it at 30 feet below the surface. The hydraulic conductivity of the clean sand aquifer is 1000 gal/day/ft^2.

Although flow occurs across the unit boundaries between the confining units and the aquifer, one can often ignore these flows because aquifer flows are so much greater. The following variables are known and can be plugged into Darcy's Law:

Aquifer hydraulic conductivity	K = 1000 gal/day/ft^2
Geometric data: distance between wells	L = 5280 ft
Aquifer cross-sectional area	= 1500 ft X (75 ft - 40 ft)
	= 1500 ft X 35 ft.
	A = 52,500 ft^2
change in the potentiometric surface	I = (30 ft - 15 ft) / 5280 ft

The aquifer is saturated, since "potentiometric surface" data given

Q = (1000 gal/day/ft^2) X (0.0028) X 52,500 ft^2
Q = approximately 149,150 gal/day

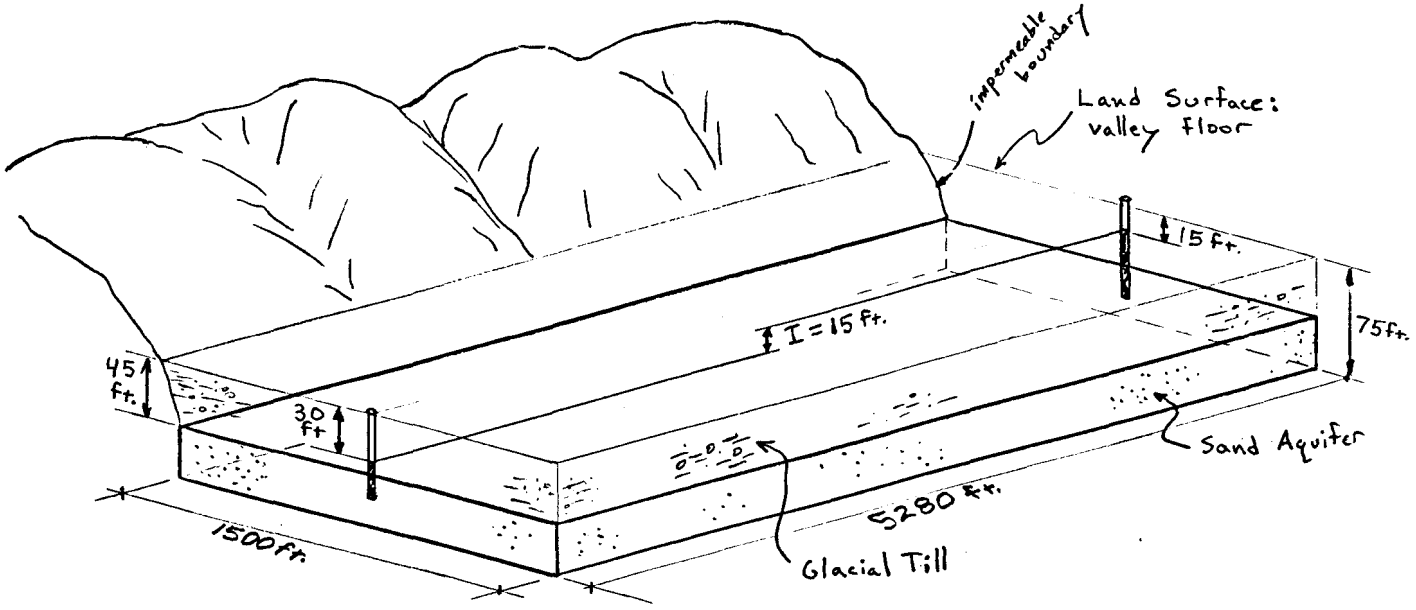


Fig. 21: Oblique and transparent view of valley sediments and geometry for Part B. Sediments are horizontal.

UNIT A

EXERCISE A2: The Relationship Between Shallow Water Level Contours and Flow Direction

Introduction

Shallow water-level contours, also called equipotential lines, show the distribution of water in an aquifer at varying hydraulic heads (potential well-heights). Water in areas where the potentiometric surface is higher will move towards areas where it is lower. Since ground-water flow occurs between areas of differing heads, there is no flow parallel to equipotential lines. The hydraulic gradient exists perpendicular to equipotential lines and flow occurs perpendicular them. Flow occurs in 3 dimensions, and equipotential lines are actually curving surfaces, but appear as lines when studied from the direction perpendicular to flow.

Objective

The objective is to gain a better understanding of how the potentiometric surface can be graphically presented and what other information can be obtained from that display. The relationship between the potentiometric surface elevation, hydraulic gradient, and the direction of ground-water flow will be investigated. This exercise is a classic three-point problem, typical of one found in structural geology.

Supplies and Equipment Required

Ruler with metric and inch scales, protractor, calculator, notebook paper, and pencil.

Task

Find the shallow water level contours between 3 observation wells, determine water level contours and the local flow direction, and mathematically calculate hydraulic gradient.

Method

Determine the water level in 3 observation wells under stable conditions. This water level must be corrected for any variations in the surface elevations at the wells if the area under study is not perfectly flat. The water level (level of the potentiometric surface) in this case is given as elevation above mean sea level (MSL).

1) Straight lines have been drawn connecting the 3 wells (seen as points) on a map. The result will is a triangle.

2) Determine the drop in elevation (hydraulic head) between the 3 wells. There will be 3 different numbers, each the number of feet difference measured along the connecting lines. These numbers should be written next to their representative connecting line. These numbers are the number of imaginary contour lines (at 1 foot intervals) that cross this particular connecting line. We will only draw the contour lines at 5 foot intervals.

3) A graphical method has been used to divide each connecting lines into the same number of equal segments as there are feet of head drop between well on each connecting line. A line perpendicular to a connecting line is drawn from each of the well points away from the triangle, but only 1 line per connecting line.

3) A convenient ruler measure is picked that will span from the well point opposite of a perpendicular line, to the perpendicular line (this is the scale line). This scale line is necessarily longer than the connecting line it will be dividing into equal segments. In this case the centimeter scale was used, and either the centimeter or half-centimeter marks were chosen (to match the number of feet head drop). There are three additional triangles now lying outside of the original 3 well point triangle.

4) All the ruler marks are marked with a tick on the scale line. There are as many tick marks as number of feet head drop between the 2 wells whose connecting line is being prepared for contour marking. Each tick mark representing a specified contour interval are marked darker. Marking of contour intervals can begin at either well point; the net result must be the same.

5) The scale markings are made on the scale line have been transferred back to the connecting line by laying a ruler perpendicular to the original connecting line across to each scale line darker (contour interval) tick mark. Only the portion where the ruler crosses the connecting line is marked on the connecting line.

6) The corresponding contour interval can be written down next to the tick marks transferred to the connecting lines. When this is completed there will be 2 contour elevations, 1 each on a different connecting line. These represent points of equal elevation on the potentiometric surface. Therefore they can be connected by a darker line passing through each point. There will be a corresponding contour interval mark on another connecting line for each contour interval mark. Connect all points up to their matching point. A pattern should immediately become apparent: All equipotential (water-level contour) lines are parallel to one another. These represent the surface in much the same way as do topographic lines on a surface map.

7) The ground-water flow direction is in the down-gradient direction perpendicular to an equipotential line. These are all parallel. Draw the line for the flow arrow (including arrowhead) near the center of the original triangle, perpendicular to elevation contour lines. The north direction arrow can be extended downward and the bearing (angle between the flow direction arrow and north) can be measured.

The worksheet and solution answer sheet, showing connecting line division units and methods, equipotential lines, and the flow direction, are on the following pages.

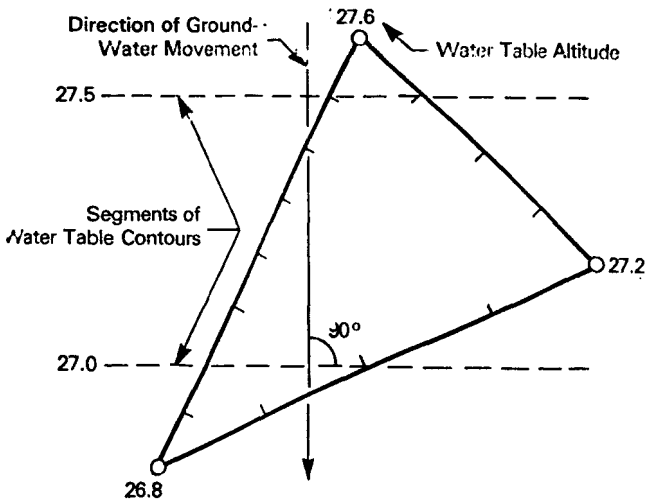
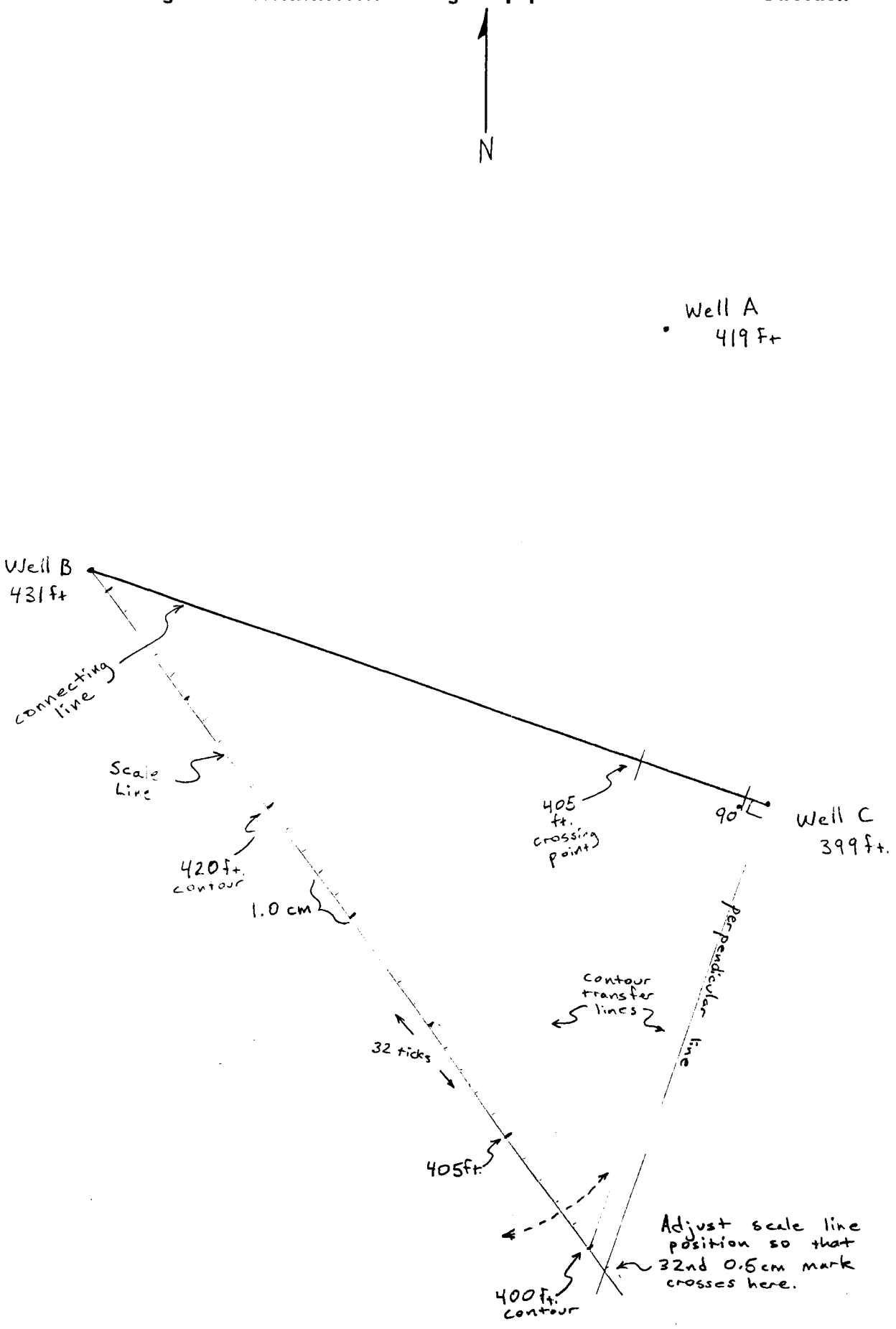


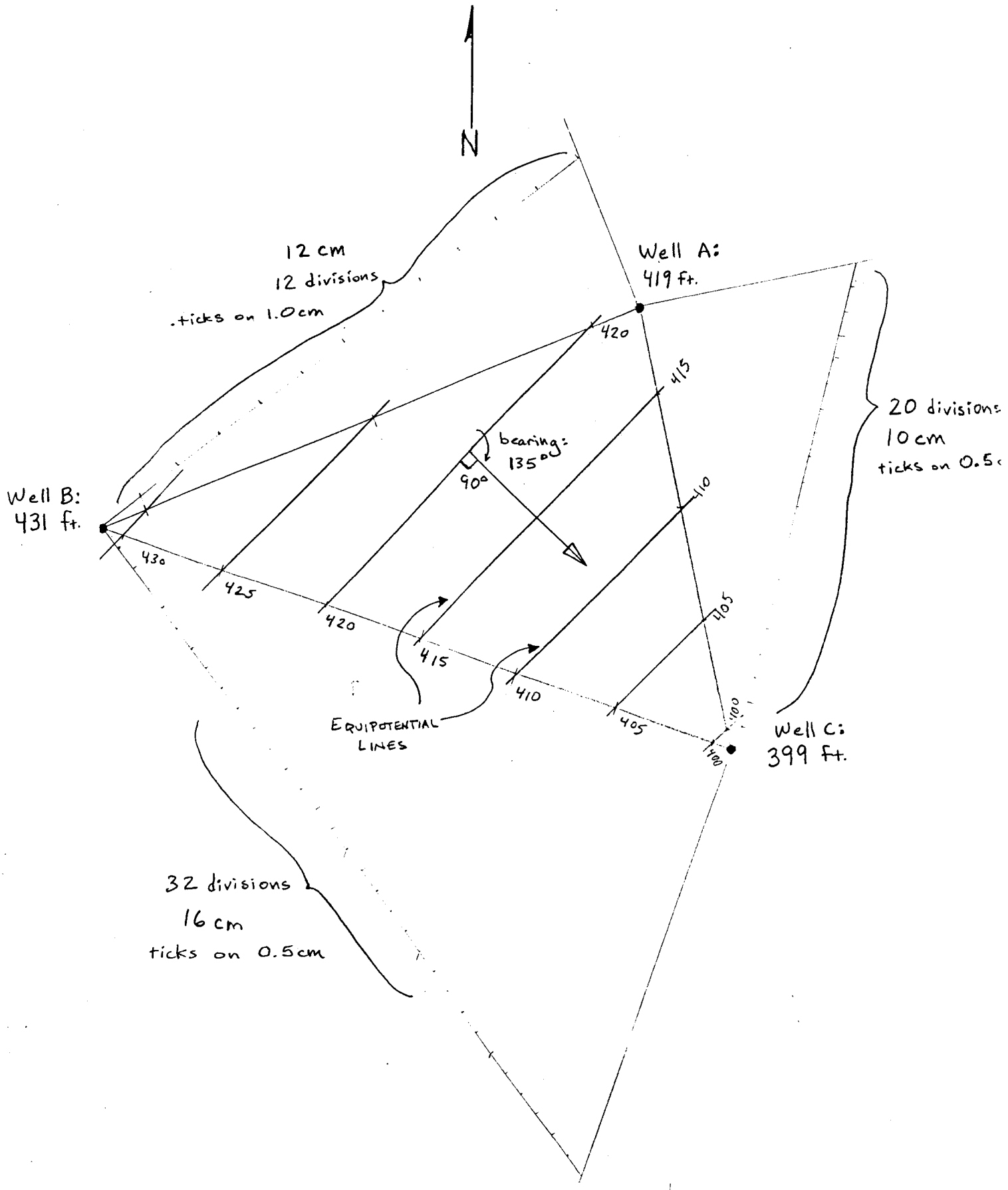
Figure 22: Plan view of 3 well points with water elevation data. Water table contours have been mapped and the flow direction drawn in (after U.S. EPA, 1987)

UNIT A / EXERCISE A2: Shallow Water Level Contours and Flow Direction

Figure 23: Worksheet for Drafting of Equipotential Lines and Flow Direction



UNIT A / EXERCISE A2: Shallow Water Level Contours and Flow Direction



Answer Sheet Showing: Connecting Line Division Units and Methods
Equipotential Lines
Flow Direction

UNIT A

EXERCISE A3: Mapping the Potentiometric Surface

Introduction

An understanding of the potentiometric surface is crucial for further study of ground water and subsurface contaminants.

Objective

This exercise attempts to bolster understanding of the concepts of potentiometric surface and water table by having you draw a potentiometric map using water-elevation data from a number of observation wells and several surface water bodies. The following rules regarding equipotential lines must be followed if an accurate map is to be constructed:

1) equipotential lines do not cross
2) equipotential lines do not originate from the center of a map, but only at the boundary areas of the map.
3) if an equipotential line does not intersect a boundary it must create an enclosed shape; the line must be connected to itself with no breaks (see #2 above).

Supplies and Equipment Required

Pencil and eraser

Task

Generate a potentiometric map using the static well-water level data listed next to the well points drawn on the following sheet. The contour interval is 5 feet. The wells are observation wells, or wells where pumping was stopped and a steady water level achieved before the measurements were taken. The data are given in elevation above sea level so that variations in surface elevations were factored out.

The rules governing potentiometric lines are listed above. Figure 25 shows a sample map as an example. The position of a equipotential line between 2 well points only occurs if a contour interval falls somewhere between their respective elevations. If this criterion is met, the closeness of the line to 1 well point versus another should be a best estimate of the process followed in Exercise A2. However, the contour lines will not be straight lines, because this map covers a much broader area typical of a hydrological site study.

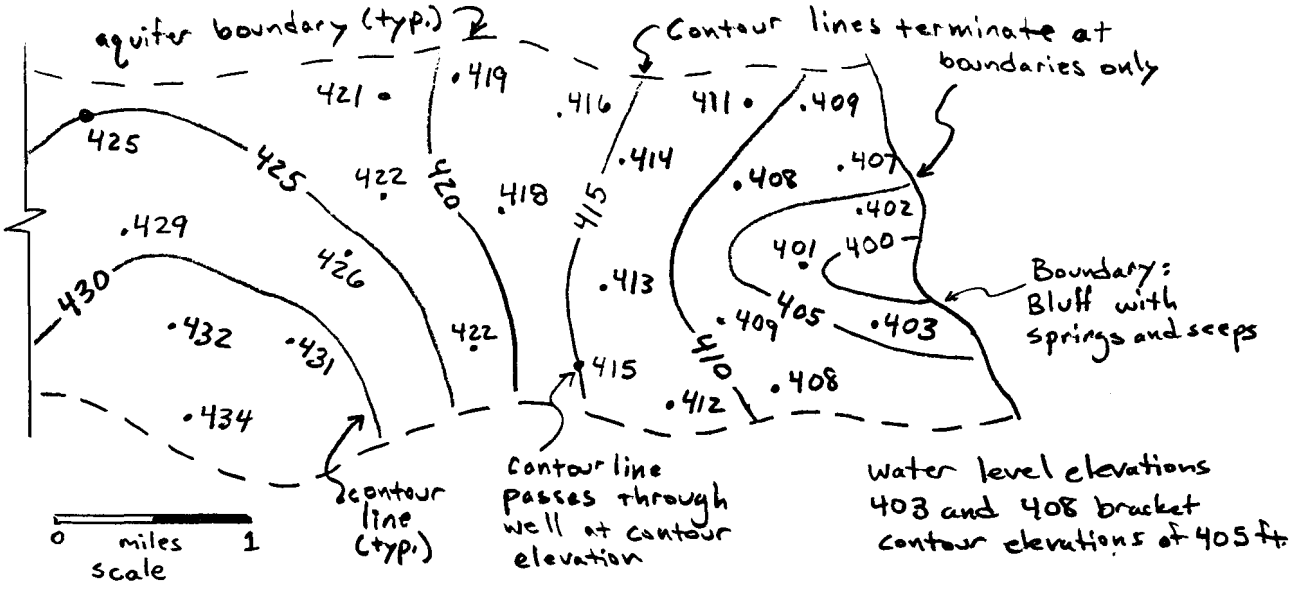


Fig.25: Sample potentiometric map illustrating properties of potentiometric lines and showing well point water elevation data and contour lines proportionally spaced per well data.

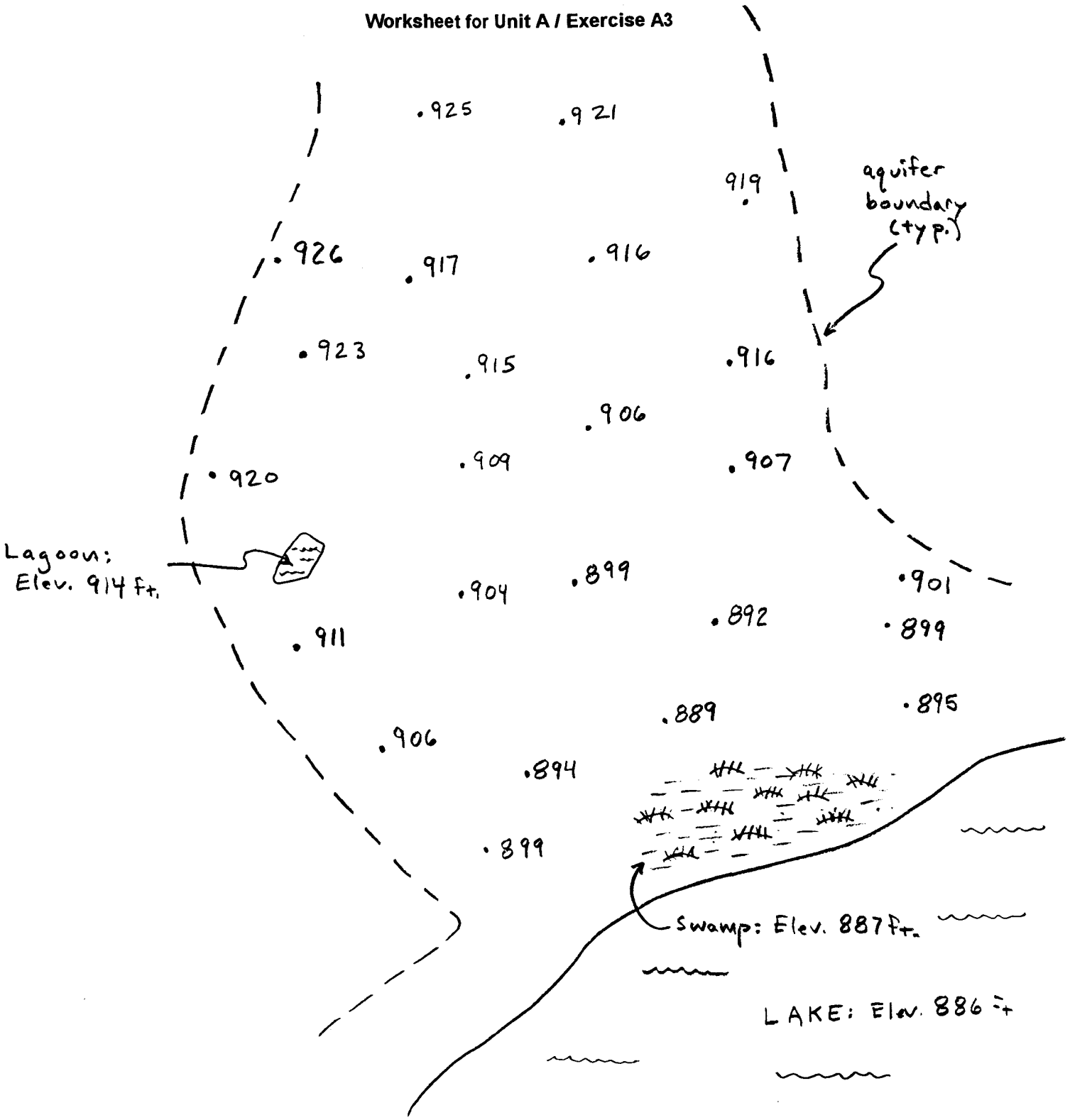


Figure 26: Worksheet for Unit A / Exercise A3. Map view of observation well water level data, given as elevation above sea level. Aquifer boundary conditions are shown.

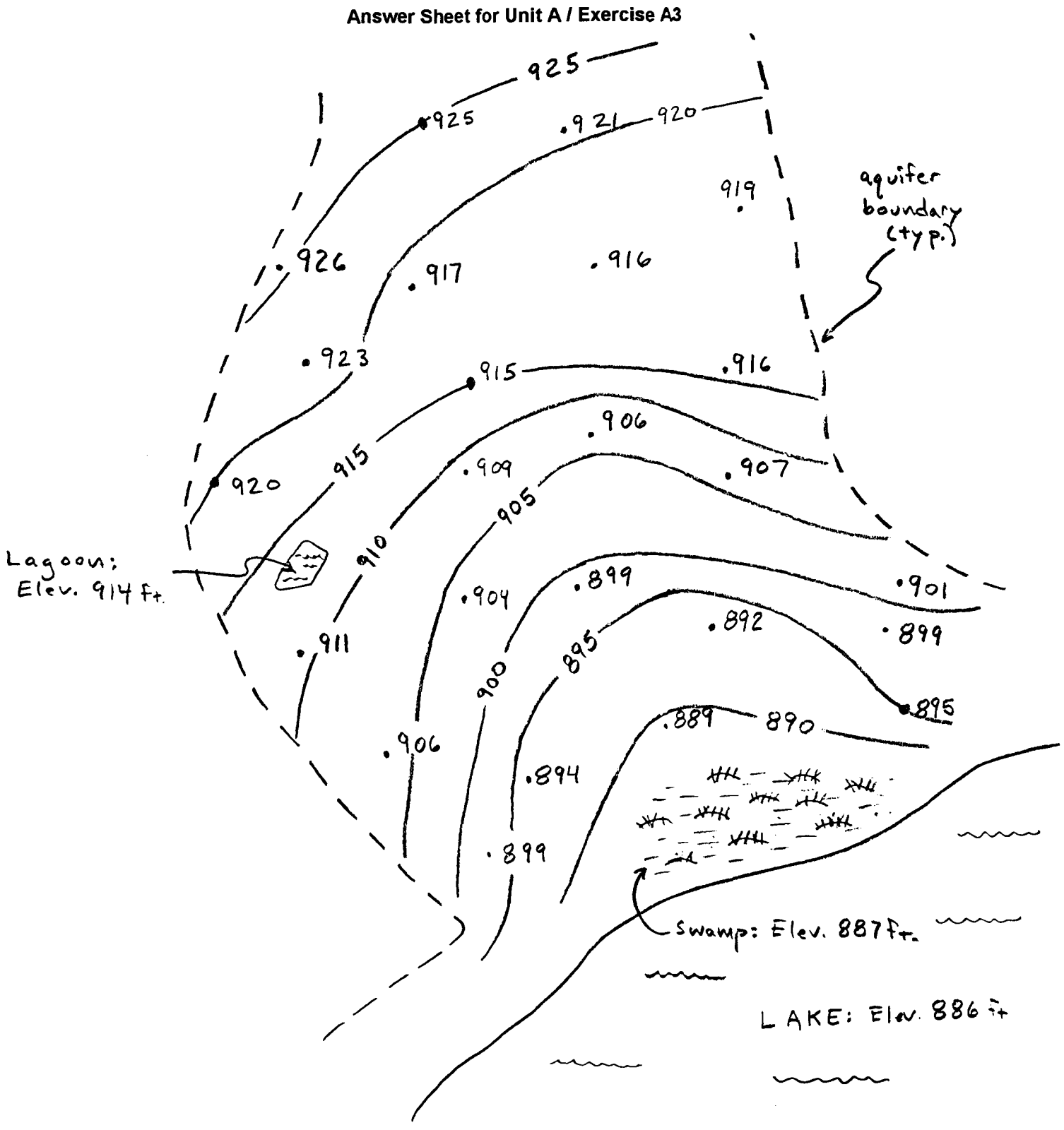


Figure 27: Answer sheet for Unit A / Exercise A3. Map view of observation well points and shallow water level contours drawn in, describing the potentiometric surface.

Appendix II

Exercises for Unit B

UNIT B

EXERCISE B1: Contaminant Plume Movement

Introduction

The concept of how quantitative values for porosity affect calculations involving the actual measured (quantitative) value for porosity will be introduced here. Actually, flow through rocks or soils only occurs between grains of geologic material, not though the grains or particles. This flow is called interstitial flow and is determined by the effective porosity.

Effective porosity is the percent of the total volume of a given mass of rock or soil that consists of interconnecting pores or voids. A pore is not a conduit for flow if it does not communicate with adjacent pores, if those pores do not interconnect with others, and so on. For net flow (advection) to occur pores must interconnect, however tortuous the flow path may be.

Objective

The objective is to see how the rate of movement of a contaminant plume can be calculated and to examine the roll that effective porosity, a measurable (and somewhat predictable) quantity, plays in predicting the rate of movement of a contaminant plume.

Supplies and Equipment Required

Calculator, pencil, and notepaper.

Task

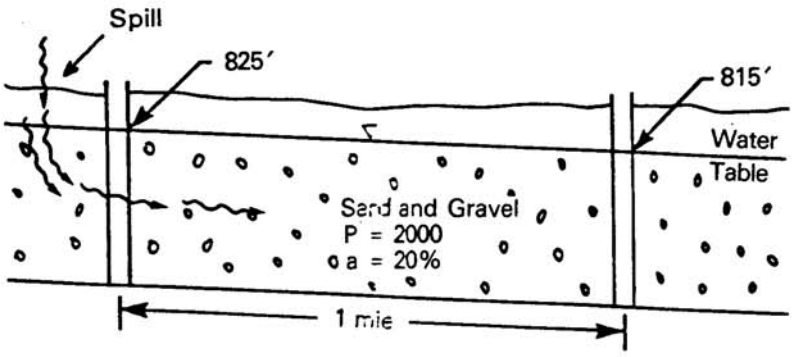
Read through the following contaminant release scenario and assemble the data required to operate the equation and calculate the time required for the plume to reach the next well. This problem is from the U.S. EPA, 1987.

A conservative substance, chloride in this case, has been spilled. The waste liquid has infiltrated the unsaturated zone and begun dissolving into the aquifer water table. The aquifer consists of sand and gravel with a hydraulic conductivity of 2,000 gal/d/ft^2 and an effective porosity of 0.20. The water table in a well adjacent to the spill site is at an elevation of 1,525 feet. A well one mile directly downgradient has a static water level of 1,515 feet.

Determine the velocity of the water and contaminant (assume virtually no dispersion), and how long it will be before the second well is contaminated by chloride. A modified form of Darcy's Law will be used, with the conversion constant for converting gallons to cubic feet: 7.48 ft^3 per gallon. The modified formula for velocity is $\mathbf{v = KI / 7.48n}$.

Where v = interstitial velocity
n = effective porosity
K = hydraulic conductivity
I = hydraulic gradient

The scenario is illustrated in the cross sectional diagram (Figure 28) on the next page, along with the solutions and calculations.



$$V = \frac{PI}{7.48a} = \frac{2000 \times \frac{10}{5280}}{7.48 \times 0.2} = \frac{3.8}{1.5} = 2.5 \text{ ft/day}$$

$$\text{Time} = \frac{5280'}{2.5 \text{ ft/day}} = 2112 \text{ days or } 5.8 \text{ years}$$

Figure 28: Cross section of spill scenario described in Unit B / Exercise B1. The spill location relative to the two wells is shown (U.S. EPA, 1987)

$v = KI / 7.48n$

n = effective porosity
K = hydraulic conductivity
I = hydraulic gradient
$v = (2000 \text{ gal/d/ft}^2) \text{ X } (10\text{ft} / 5280 \text{ ft}) / 7.48 \text{ X } 0.20$

The velocity is 2.5 feet per day

Time equals the distance that must be covered by the velocity:

$T = 5280 \text{ ft} / 2.5 \text{ ft/day}$

T = 2112 days or 5.8 years

The time required for the spill to reach the other well is 5.8 years.

UNIT B

EXERCISE B2: Contaminant Plume Shapes

Introduction

The shape of a contaminant plume depends on a variety of factors. The text has concentrated on advection, dispersion, the type of contaminant, and the retardation processes. Another important factor is the length of time and any interruptions in the spillage or leakage of contaminant to the subsurface. Refer back to Unit B, Figures 10 and 16, a and b, to review helpful information that has been presented previously.

Objective

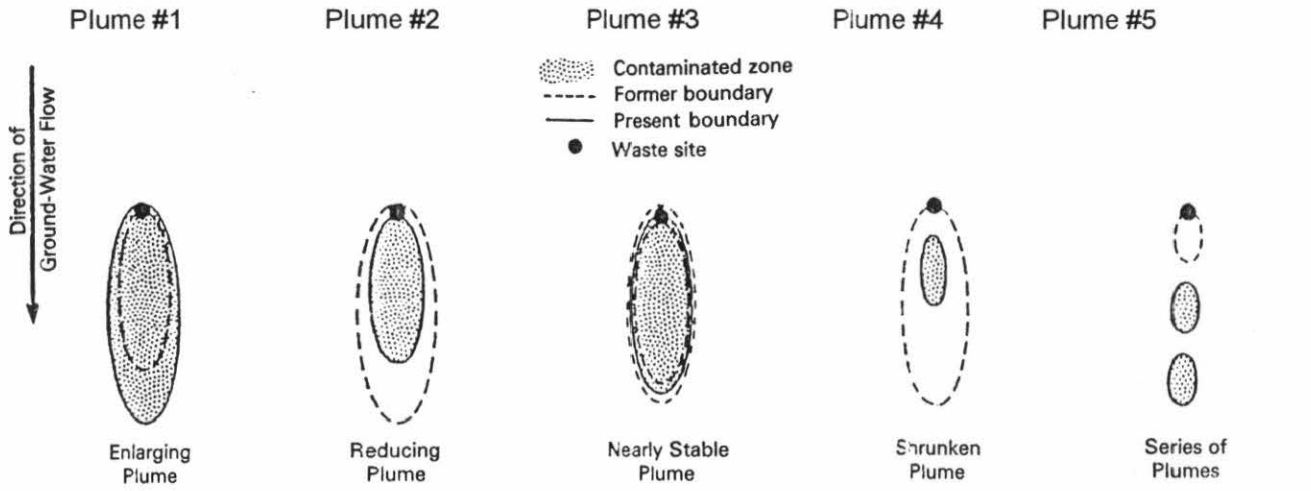
Illustrate some of the temporal (time) factors affecting contaminant releases and how they can be manifest in plume shapes.

Supplies and Equipment Required

Pencil or pen

Task

Match the four following contaminant plume shapes to the sets of possible causes listed below in Figure 29. The answers are given on the following page in Figure 30.



SET A

1. Essentially same waste input
2. Sorption capacity not fully utilized
3. Dilution effect fairly stable
4. Slight water-table fluctuation or effects of water-table fluctuation not important

SET B

Intermittent or seasonal source

SET C

1. Increase in rate of discharged wastes
2. Sorption activity used up
3. Effects of changes in water table

SET D

1. Reduction in wastes
2. Effects of changes in water table
3. More effective sorption
4. More effective dilution
5. Slower movement and more time for decay

SET E

Waste no longer disposed and no longer leached at abandoned waste site

Figure 29 Plan view illustrating possible plume size and shape fluctuations due to various factors (after U.S.EPA, 1987, modified from U.S. EPA, 1977)

EXERCISE B2: Contaminant Plume Shapes

Answers to exercise on following page

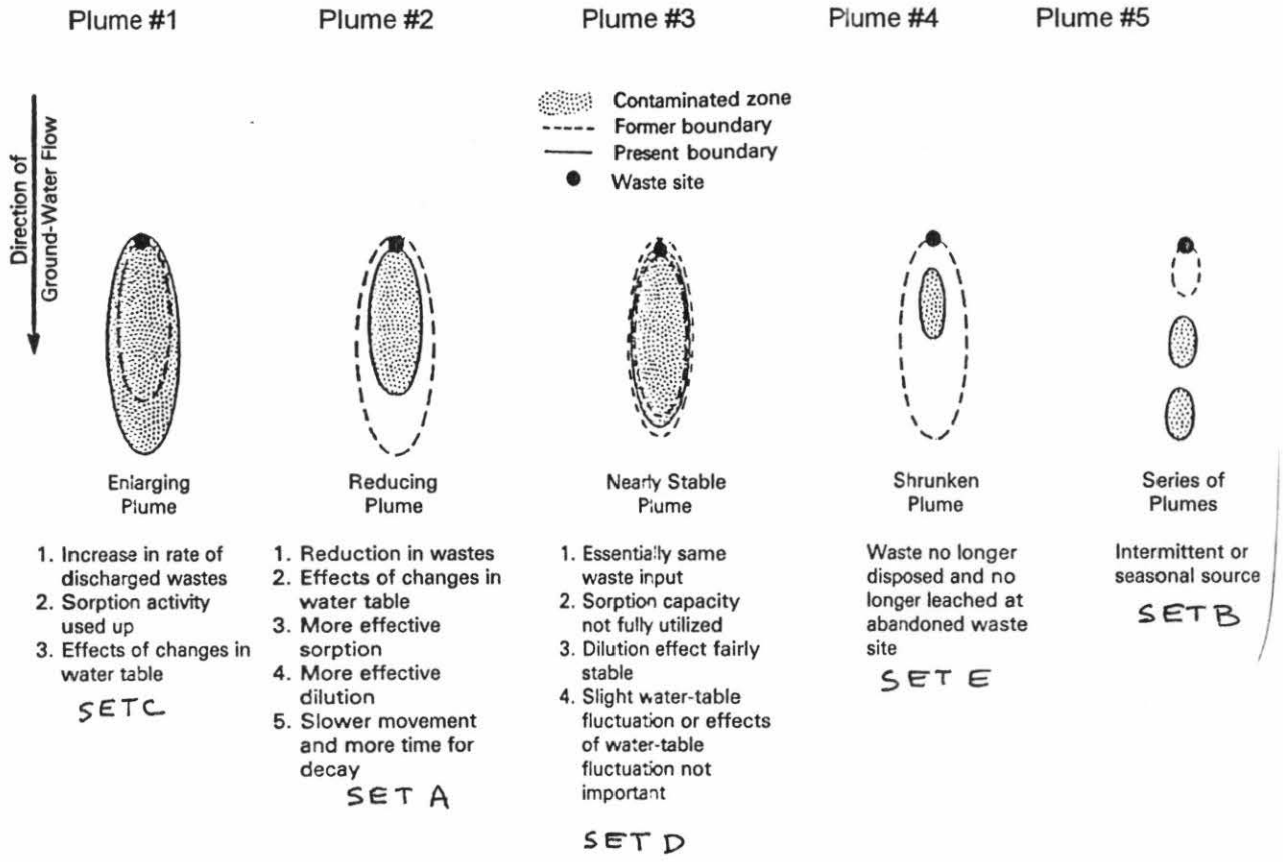


Figure 30: Plan view illustrating possible plume size and shape fluctuations due to various factors (after U.S.EPA, 1987, modified from U.S. EPA. 1977).

Discussion

The enlarging plume is evidence of increased amounts of contaminants being entrained into the ground water. This can be due to reduced release of contaminants, just as an increasing contaminant amounts could reflect increasing release.

Water table elevation affects the amount of contaminant dissolving into it in the following manner: Contaminants can be present in residual saturation amounts in the unsaturated zone. For this part of a contaminant release to reach the water table, water (from either infiltration or water table level rise) must come into contact and dissolve the soluble portions of the plume. If the water table falls, the dissolved plume can be expected to become smaller.

A stable plume reflects stable conditions, while a shrunken plume indicates that methods to reduce the contamination are working, or that the contaminant releases have stopped. The intermittent plume indicates periodic releases, rather than continuous release. This can be due to human factors (eg. an industrial operation performed only once a year) or can be the result of yearly variations in rainfall infiltration or major water table changes.

UNIT B

EXERCISE B3: Remediation Problems and Strategies for NAPLs

Introduction

This exercise investigates several NAPL plume physical properties in the subsurface. As discussed before, NAPL contaminants present different and very difficult set of problems regarding containment and cleanup.

Objective

Review the figures included within this exercise concerning NAPLs and DNAPLs. Study the schematic of a NAPL release site and generate a possible scenario of plume movement, and list possible methods for dealing with the contamination.

Supplies and Equipment Required

Tasks

Study Figure 31. The left-hand storage tank contains DNAPL, with a density greater than that of water. The right-hand tank contains LNAPL, having a density less than water. The releases are due to leaks in the respective storage tanks. Note the geometry of the confining bed below the aquifer and the ground-water flow direction. Sketch the possible paths, shapes, and final location of the LNAPL dissolved and free-product plumes on Figure 32. Assume that a large amount of material was released over time. Review of Figures 33 through 37 concerning DNAPL plume behavior in the subsurface will provide hints as to the possible plume behavior.

Questions

1) What problems might be encountered during a site assessment?

2) What would happen if the confining bed shown at the bottom were much deeper?

3) What methods of containment or remediation might be used to combat this environmental problem?

The answer keys are on the following pages.

EXERCISE B3: Remediation Problems and Strategies for NAPLs
Diagram showing answer for plume sketch problem

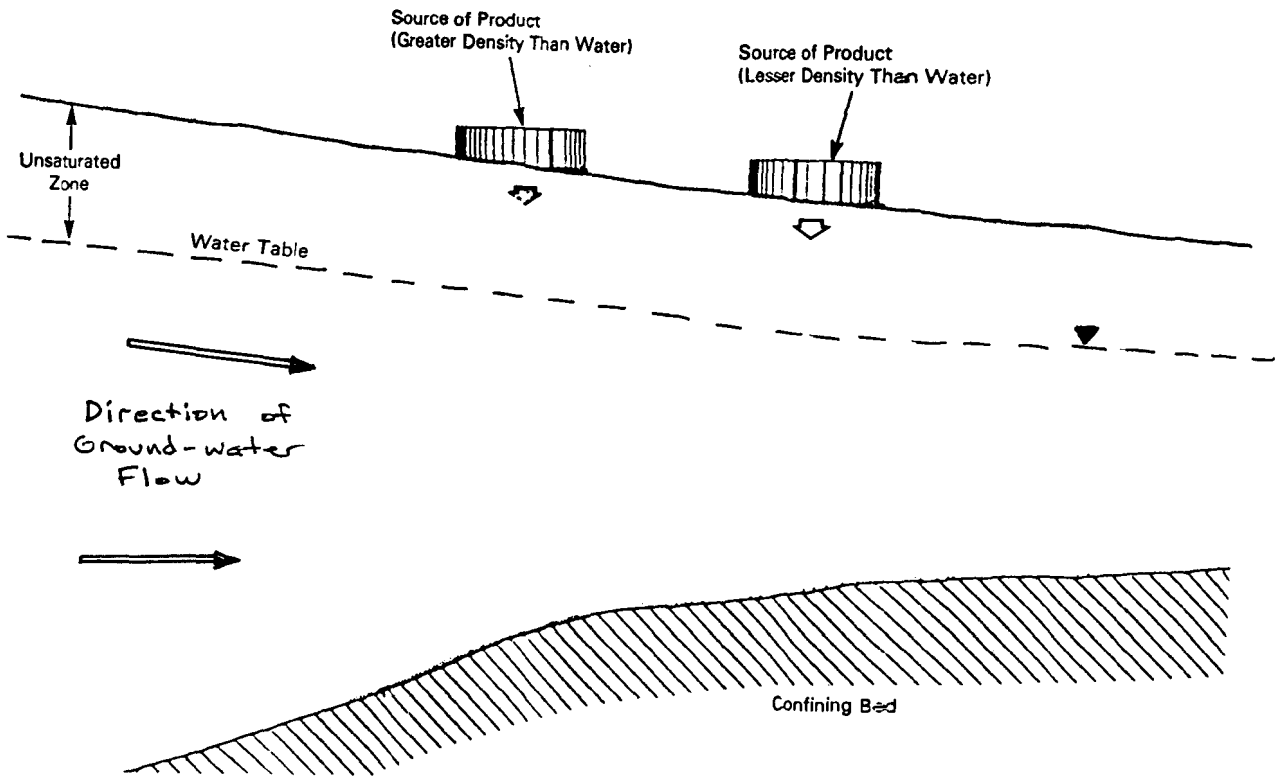


Figure 31: Worksheet showing cross section of aquifer, water table, and ground-water flow for Exercise B3 (after U.S. EPA, 1987).

EXERCISE B3: Remediation Problems and Strategies for NAPLs
Diagram showing answer for plume sketch problem

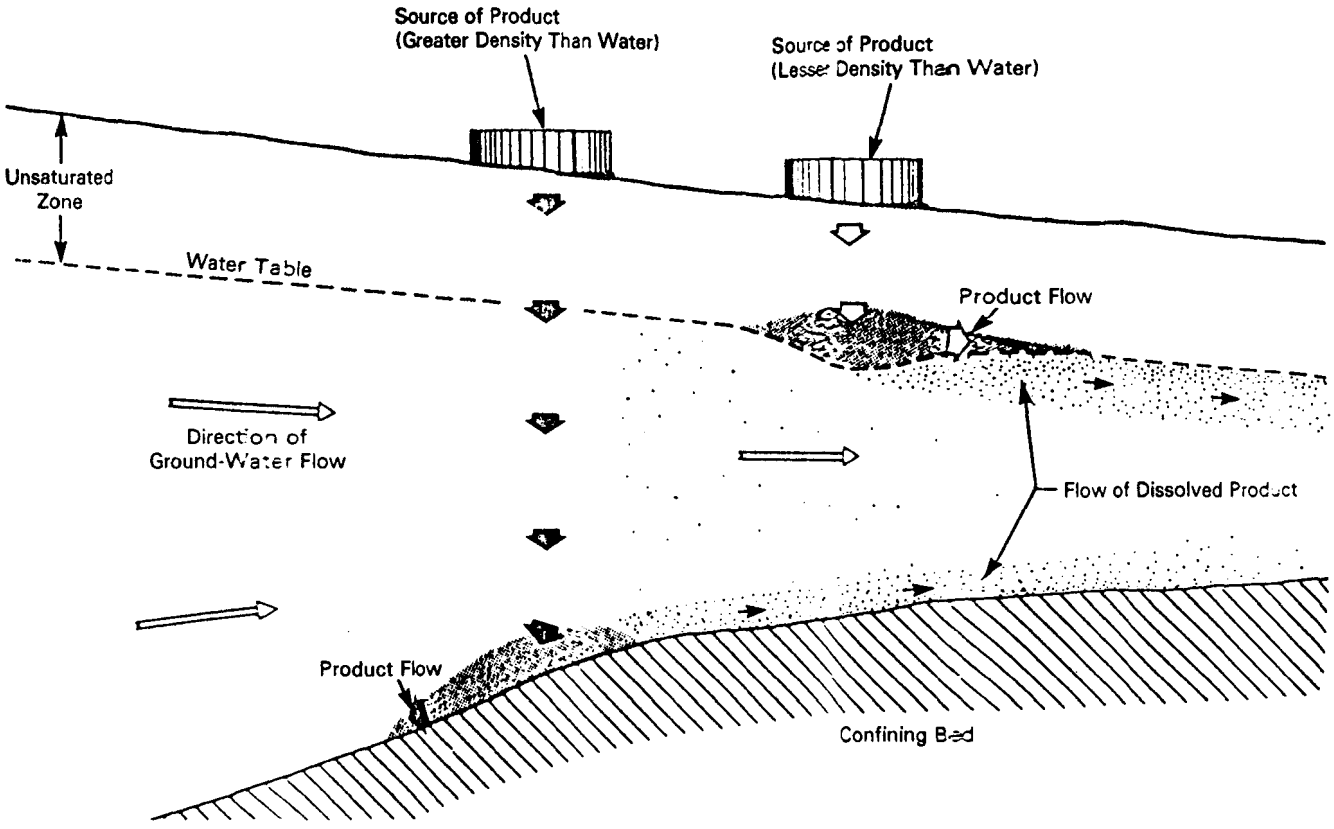


Figure 32: The possible shape for the contaminant plumes are shown (U.S. EPA, 1987).

Answers to Questions for Scenario in Exercise B3:

1) What problems might be encountered during a site assessment?

NAPLs may not be suspected as the source of dissolved contamination. The plume could be contributed to the wrong source if the tanks shown are on a large industrial site with many other chemicals in use. If the DNAPL and LNAPL contribute some of the same dissolved compounds to the aquifer, only one NAPL might be suspected and remediation centered on only the one type. The pools that form when a large quantity reaches (and penetrates, in the case of DNAPL) the water table may not be found in a limited evaluation using only a few observation wells. The DNAPL plume could be mistaken to be traveling in the direction of local ground-water flow, rather than down the slope of the confining bed.

2) What would happen if the confining bed shown at the bottom were much deeper?

The confining bed serves to keep the plume from penetrating deeper into the subsurface. Plumes are generally easier to control and remediate when they are closer to the surface. For example, subsurface barriers can only be installed up to a certain depth. A deep-penetrating plume has a better chance for contaminating regional ground-water flow and moving greater distances. This usually means off the contaminant release site and perhaps into more sensitive areas or surface bodies of water (U.S. EPA, 1991)

3) What methods of containment or remediation might be used to combat this environmental problem?

The initial approach would be to prevent the spread of the free-phase product, thereby reducing the amount of aquifer material contaminated to residual saturation levels. If the confining bed is close enough to the surface (per the claims of the manufacturer), a subsurface barrier could be installed to stop the DNAPL plume from moving down-slope. This barrier might also be able to block ground-water flow into the plume area, reducing the amount of dissolved contaminant spreading away from the main plume. The barriers would probably be used in conjunction with hydrodynamic controls to ensure containment. Barriers might be used primarily to control movement of uncontaminated water into the plume area. If barriers were impractical, hydrodynamic controls would be the only means to control movement of the plume.

There is the chance that active withdrawal and treatment (pump-and-treat) could be practical for the site. In this case an attempt would be made to access the free-product pools as well as the dissolved phase and soil gases (if any).

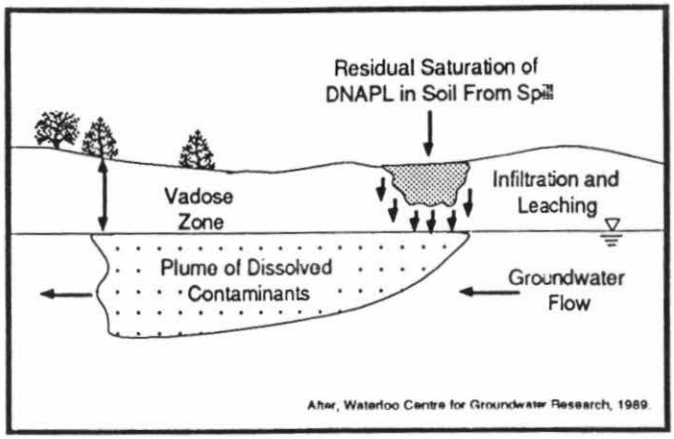


Figure 33: DNAPL of insufficient volume to completely saturate the unsaturated zone and reach the water table. DNAPL mass is exhausted before free-product phase reaches the water table, but soluble components are able to contaminate ground water (U.S. EPA, 1991).

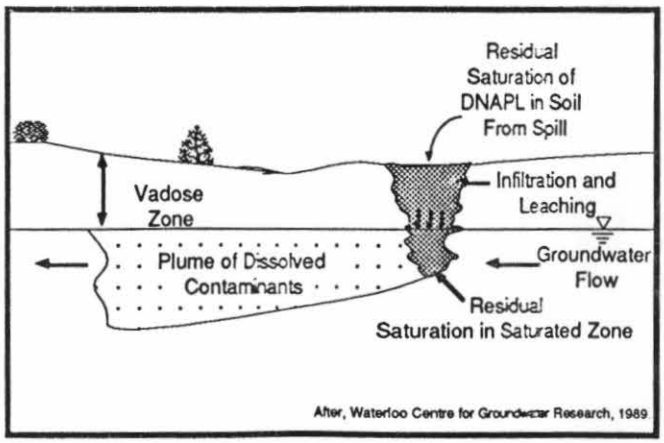


Figure 34: DNAPL release of sufficient volume to overcome residual saturation in the unsaturated zone and consequently penetrate the water table (U.S. EPA, 1991).

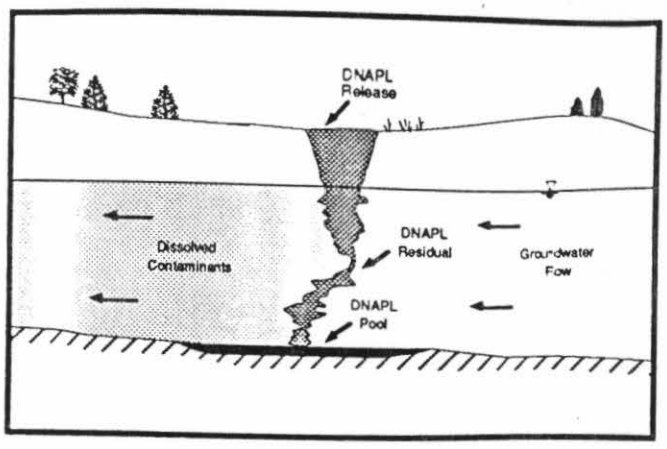


Figure 35: Migration of DNAPL through the unsaturated zone to an impermeable boundary (U.S. EPA, 1991).

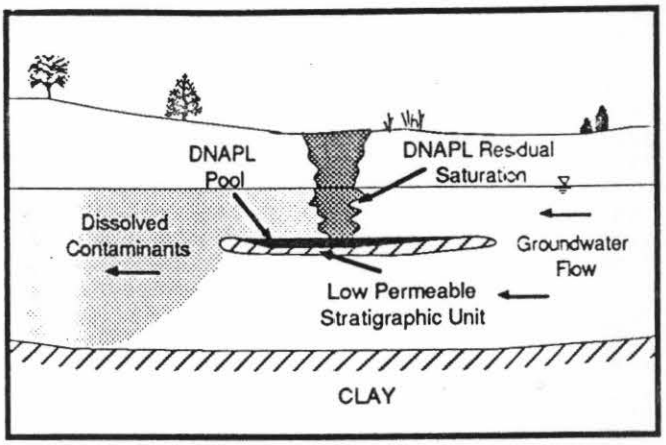


Figure 36: DNAPL in free-product form as a perched reservoir (U.S. EPA, 1991).

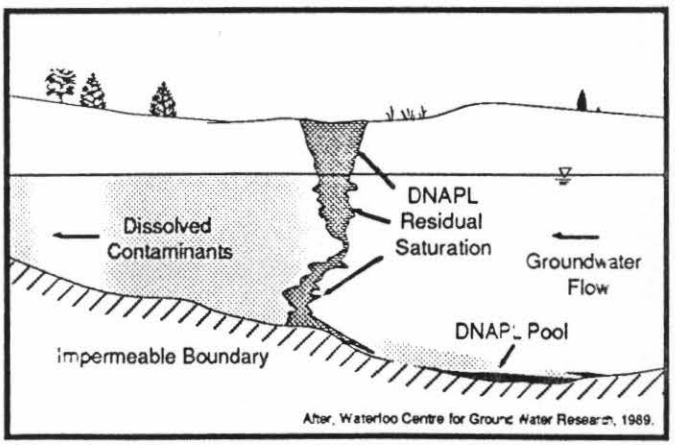


Figure 37: Confining bed tipped geometry causing flow of DNAPL in direction different than that of ground-water flow. Note that the dissolved plume movement is within the ground-water flow (U.S. EPA, 1991).

Appendix III
Glossary

advection - flow of ground water and/or contaminants due to hydraulic gradient and gravity. The dominant transport process for ground water and all soluble contaminants.

aeration, zone of - (see unsaturated zone)

capillary fringe - the volume of material located just above the saturated zone. It is saturated, but at negative atmospheric pressure, in place due to the wicking action of pores

contaminants - all physical (including radioisotopes and biological particles) and chemical solutes introduced into the hydrogeologic environment due to human activity (after Freeze and Cherry, 1979); can come from both natural and man-made sources;are considered "pollution" when concentration increases above a certain level (quality standard).

DNAPL - an acronym for "dense nonaqueous-phase liquid", synonymous with dense (relative to water) immiscible-phase liquid (hydrocarbon). The movement of DNAPLs in the subsurface is difficult to predict, as their movement is determined by properties different from those of ground water (see NAPL).

density - the mass (or weight) of a substance per unit volume, which can also be expressed as a (unitless) ratio as compared to water, eg. a compound having a ratio of 1.15 is denser than water (with a density of 1.00) and would sink.

diffusion (molecular diffusion) - the spreading out of molecules or ions into a fluid or porous medium in a direction tending to equalize concentrations in all parts of the system. [Produced by differences in chemical concentrations which tend to be erased in time by random molecular motion; works together with dispersion.]

dispersion (hydrodynamic dispersion) - spreading of a plume produced by natural differences in local ground-water velocities related to local differences in permeabilities. [Works together with diffusion.]

discharge - the loss of water from an aquifer or zone of saturation, such as withdrawal, draining, evapotranspration, seepage, etc.

discharge rate - stream flow, well flow. [units are a volume (or quantity) per unit time, such as gallons per minute (gpm).]

drawdown - the lowering in height of the water table (and water level in a well) on a local or regional scale due to pumpage (withdrawal) from an aquifer; a measure of height (length), the reduction in hydraulic head due to withdrawal of water from a well.

ground-water flux rate - flow rate per unit area; a discharge rate, also known as the bulk flow rate [units are gal/day, symbol is Q.]

ground-water flow rate - volume of water flowing, units are gal/day.

hydraulic conductivity - a measure of the ability of medium to transmit water, units are ft/day [also gal/day/ft^2], symbol is K or p. Permeability is a qualitative term for hydraulic conductivity.

hydraulic gradient - the slope of the water table or potentiometric surface, the change per unit distance, the driving force for ground-water movement. [Units are feet per foot, symbol is I.]

hydraulic head - the difference in elevation of water level between two points, given as distance unit; denotes pressure differences affecting flow in ground-water systems, [symbol is h.]

immiscible contaminant - a contaminant that is composed of entirely or predominantly immiscible (not mixing with water) liquids; forms a distinct boundary when mixing with water is attempted. However soluble components are able to dissolve into ground water (see NAPLs).

interstitial velocity - the velocity of water and/or contaminants in interconnected pores, taking into account that advection does not occur through the grains (solids).

ion exchange - the exchange of ions of a contaminant/ground-water solution with geological materials present in the subsurface, usually controlled (and possibly reversed) by changes in pH and chemical conditions.

LNAPL - an acronym for "light nonaqueous-phase liquid", synonymous with less dense (relative to water) immiscible-phase liquid (see NAPL).

NAPL - acronym for nonaqueous-phase liquid; a hydrocarbon that when mixed with water results in a physical interface between the two liquids. This interface divides the two liquids, but compounds in the NAPL are not prevented from dissolving into ground water. [See dense NAPL (DNAPL) and light NAPL (LNAPL).]

partitioning - the entrapment of a portion of a NAPL in continuous-phase form in the pores of a geological material when in the presence of water. The NAPL becomes immobile in the small pores, or in large pores when flow slows relative to that in smaller pores.

porosity - the ratio of open pore spaces in a rock or soil to its total volume, defines amount of water or liquid a rock can contain. [Expressed as a percentage or decimal fraction, symbol is θ (theta), term is unitless.]

porosity, effective - the percent of the total volume of a given mass of rock or soil that consists of interconnecting pores or voids, symbol is n.

potentiometric surface - the water table surface or level (or potential surface, if not in a confined unit), can be expressed in graphical form as a potentiometric surface map of equipotential lines, similar to topographic lines; also called the piezometric surface.

recharge - the addition of water (refilling) to an aquifer or zone of saturation, such as rainwater infiltration, or seepage from a river or pond.

remediation - general term referring to activities undertaken to improve a contaminant problem and to prevent the worsening (spread) of contamination.

residual saturation (contaminant) - immiscible-phase liquid held on the pore spaces by capillary tension; cannot be mobilized by typical hydraulic forces (local ground-water flow)

residual saturation (water) - the amount of water remaining in the pore spaces of a material when the material is allowed to drain by gravity. This amount cannot decrease below a certain threshold amount

retardation - any one of several methods that can slow or temporarily stop the spread of contaminants in ground water in the subsurface. Includes partitioning, ion exchange, and sorption.

run-off - the moisture from precipitation that does not infiltrate (soak into) the ground because of saturated or special soils. Run-off instead flows over the surface. Run-off flows along drainages and low areas.

saturation zone (ground-water zone) - the zone below the water table; all pore spaces are filled with water, contaminant, or water and contaminant

solubility - how easily a compound or component of a contaminant dissolves into water under "standard conditions", controlled by the polar character of the solute and solvent, pH, temperature, other chemicals present, etc. In general, the "heavier" and more complex contaminants have a lower solubility in water

sorption - when a dissolved ion or molecule becomes attached to the surface of a solid or dissolves in the solid; actually of two types of processes: adsorption, a surficial phenomenon, and absorption, the phenomenon involving movement of material from solution to sites within the structure of the solid phase. These reactions are usually fast and reversible.

specific yield - the amount of water a rock releases if allowed to drain by gravity, which is not the total water the rock contains; the volume available for withdrawal by wells.

unsaturated zone - the zone above the saturated zone (water table), which may contain saturated or partially saturated (with water and/or contaminants) sediments; overlies the saturated zone, the contact area between the unsaturated zone and saturated zone is known as the capillary fringe. [Also known as the zone of aeration or the vadose zone.]

velocity, interstitial (bulk velocity) - the flow of a particular front of water; how fast an advective front moves; affected by the effective porosity, hydraulic conductivity, and hydraulic gradient. [units are ft/day, symbol is v.]

water table - the surface of the upper limit of the saturation zone in an unconfined aquifer, given as an elevation above sea level or a distance below the ground surface. [Units are in length (see potentiometric and piezometric surface).]

withdrawal rate - the rate at which water is removed or pumped from an aquifer via a well, or series of wells; expressed as a volume per unit time.

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